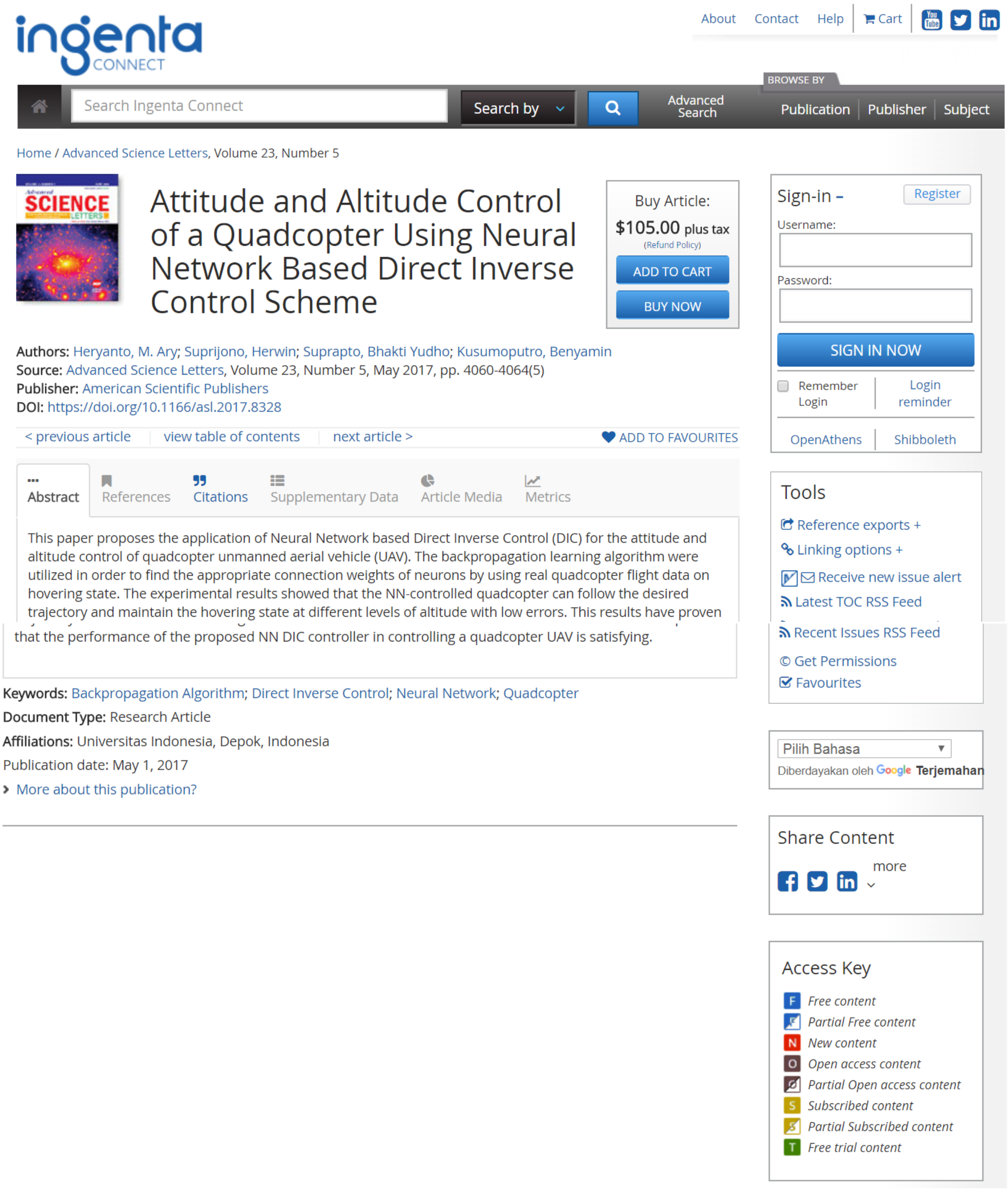

Attitude and Altitude Control of a Quadcopter Using Neural Network Based Direct Inverse Control Scheme

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This paper proposes the application of Neural Network based Direct Inverse Control (DIC) for the attitude and altitude control of quadcopter unmanned aerial vehicle (UAV). The backpropagation learning algorithm were utilized in order to find the appropriate connection weights of neurons by using real quadcopter flight data on hovering state. The experimental results showed that the NN-controlled quadcopter can follow the desired trajectory and maintain the hovering state at different levels of altitude with low errors. This results have proven that the performance of the proposed NN DIC controller in controlling a quadcopter UAV is satisfying.

Keywords: Backpropagation Algorithm; Direct Inverse Control; Neural Network; Quadcopter

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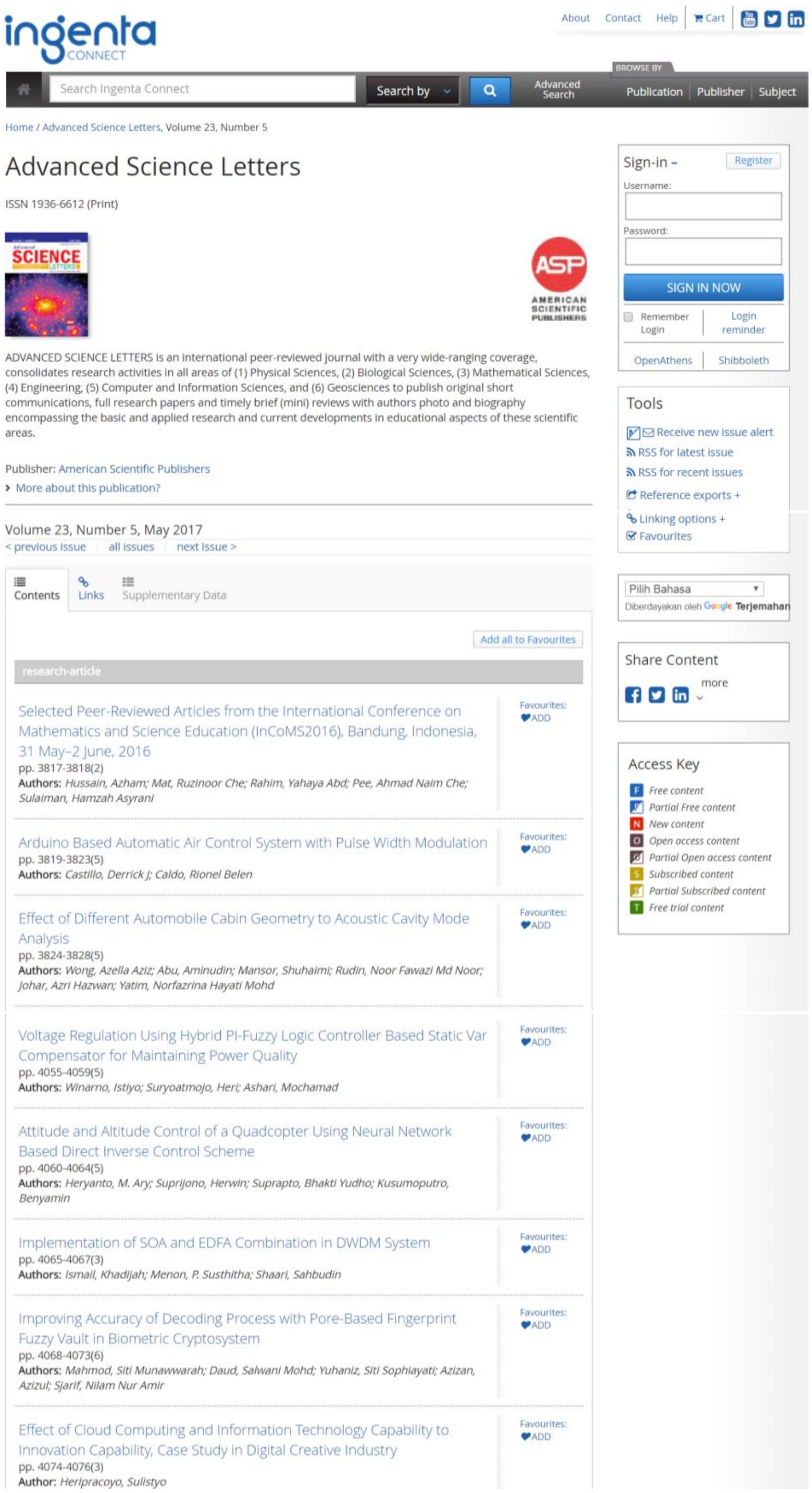

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Attitude and Altitude Control of a Quadcopter using Neural Network Based Direct Inverse Control Scheme

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This paper proposes the application of Neural Network based Direct Inverse Control (DIC) for the attitude and altitude control of quadcopter unmanned aerial vehicle (UAV). The backpropagation learning algorithm were utilized in order to find the appropriate connection weights of neurons by using real quadcopter flight data on hovering state. The experimental results showed that the NN-controlled quadcopter can follow the desired trajectory and maintain the hovering state at different levels of altitude with low errors. This results have proven that the performance of the proposed NN DIC controller in controlling a quadcopter UAV is satisfying.

Keywords: Backpropagation algorithm, Direct Inverse Control, Neural Network, Quadcopter.

1 INTRODUCTION

A quadcopter is classified as a rotary wing with four rotors located at its four corners. The advantage of this structure laid on the ability to perform Vertical Take Off and Landing (VTOL), high maneuverability along its course, and stable hovering[1,2]. Therefore, a quadcopter based unmanned aerial vehicle (UAV) provides exceptional benefits and is eligible for many civil and military applications such as aerial observation, photography, security monitor, search and rescue missions and other comparative applications [3-7].

A quadcopter is intended to have the capability as a helicopter, with a more straightforward mechanical system yet more stable in its maneuvers because of a four motors system. On the other hand, a quadcopter is a very dynamic system due to the non-linear characteristic of the plant, under actuated and cross-coupling from its gyroscopic moments of the motors[8,9]. Thus, controlling the quadcopter within a six degree of freedom (DoF) is a challenging problem.

Some of the most widely used control methods for a quadcopter are PID, LQR, and Backstepping. PID and LQR control algorithms are a linear control algorithm that is not suitable for non-linear systems, while the robustness of a Backstepping control algorithm is still questionable[10].

Some researchers have developed various neural network based control systems and all methods revealed a good performance characteristics[11-14]. In the previous studies, we have also developed a quadcopter control system using neural network-based inverse system in a Direct Inverse Control (DIC) scheme[15]. The Cross configuration quadcopter system was developed in the Computational Intelligence and Intelligent Systems Laboratory, Universitas Indonesia. The back propagation

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neural networks based inverse (BPNN-INV) control system that was used as the quadcopter controller system, however, is trained and tested by using a database taken from a stationary vertical test-bed system. As the consequence, the database obtained from this experiment is valid for a constant altitude condition only. In order to develop an autonomous BPNN-INV control system, in this paper, the neural networks based inverse system is trained by using a real data flight of the quadcopter.

This paper is structured as follows. Section 2 introduces the structure of Quadcopter, the dynamics and kinematics of quadcopter model. The experimental data acquisition is also put forward in this section. The neural network control algorithm is discussed in Section 3, followed by the elaboration of simulation results on the experimental data in Section 4. Finally, our work in this paper is summarized in the last section.

2 THE QUADCOPTER AND DATA ACQUISITION

A. Quadcopter Model

The dynamic model of the quadcopter is defined by dividing the system into two reference frames as shown in Fig. 1. A body frame (BF) is the first reference frame, where the OB (*X, Y, Z*) is chosen to coincide with the center of mass. The second reference frame is the earth frame (EF), where the OE (*x, y, y*) is the axis origin. The position and orientation of the BF or the quadcopter is described with respect to the EF reference frame[16].

The quadcopter used a fixed pitch blade at each motor, so that the motor generates an equal thrust on the quadcopter movement. The front (M1) and rear (M3) motors rotate clockwise, while the other two motors (M2, M4) rotate counter clockwise (Fig. 1), hence, these motors configuration structure canceled the rotational torque for a stable movement of the quadcopter. The movement of the quadcopter is then only controlled by increasing or decreasing the rotor speed.

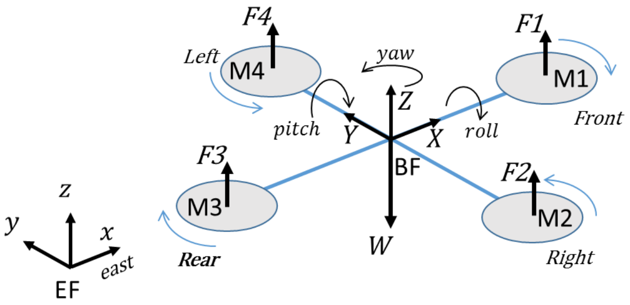


Fig. 1. Quadcopter basic movement

Increasing or decreasing the four propeller rotation at the same velocity produces an U_1 force for a vertical movement (Z_B axis), and the U_1 force generated by the same velocity of the motors has to be equal with the thrust required in a determined altitude for a hovering movement of the quadcopter. Changing the velocity of the propeller 2 and 4, respectively, i.e., Ω_2, Ω_4, creates an U_2 force for a roll (ϕ) rotation. The U_2 force produced by changing the speed of the propellers rotation makes the quadcopter rolling to the right or left in the Y_B axis, if the quadcopter is already stable by a determined U_1 force for a determined altitude.

Likewise, changing the velocity of the propeller 1 and 3, respectively, i.e., Ω_1, Ω_3, creates a U_3 force for a pitch (θ) rotation. The produced U_3 force makes a forward or a backward movement in the X_B axis. As the same with the condition in a rolling movement, the quadcopter should be in a stable condition of hovering state that the changing velocity of the propeller 1 and 3 makes the quadcopter moving forward or backward.

When making a different motor speed between each pair of 2 blades, i.e., a counter-torque is generated by the motors system, the U_4 force makes a yaw (ψ) rotation. Thus, the quadcopter is driven by four rotors that would produce a controlled thrust and torque to move from one point to others with a determined roll, pitch, and yaw moving condition. However, although quadcopter has the ability to move in a 6 DoF system, only a 4 DoF movement that are controlled directly by the four rotors[17,19].

To simplify the modeling of a quadcopter, some assumptions are adopted such as: the quadcopter structure is rigid and symmetrical, the propellers are rigid, thrust and drag forces are proportional to the square of propellers speed rotation, and the distribution of the quadcopter mass is symmetrical[20-22]. These assumptions make it difficult to develop a model of quadcopter as realistically as possible.

The equation of motion of the quadcopter is obtained using Newton-Euler formalism. The translational and rotational dynamics of quadcopter can be described by (1):

$$
\begin{aligned}
\ddot{X} &= (s\psi \cdot s\phi + c\psi \cdot s\theta \cdot c\phi)\frac{U_1}{m} \\
\ddot{Y} &= (-c\psi \cdot s\phi + s\psi \cdot s\theta \cdot c\phi)\frac{U_1}{m} \\
\ddot{Z} &= -g + (c\theta \cdot c\phi)\frac{U_1}{m} \\
\dot{p} &= \frac{I_{YY} - I_{ZZ}}{I_{XX}} qr - \frac{J_{TP}}{I_{XX}} q\Omega + \frac{U_2}{I_{XX}} \\
\dot{q} &= \frac{I_{ZZ} - I_{XX}}{I_{YY}} pr - \frac{J_{TP}}{I_{YY}} p\Omega + \frac{U_3}{I_{YY}} \\
\dot{r} &= \frac{I_{XX} - I_{YY}}{I_{ZZ}} pq + \frac{U_4}{I_{ZZ}}
\end{aligned}
\tag{1}
$$

where $\ddot{X}, \ddot{Y}, \ddot{Z}$ the linear accelerations of quadcopter with respect to EF; the $\dot{p}, \dot{q}, \dot{r}$ angular accelerations of quadcopter with respect to BF, *s* and *c* are the respective of *sin* and *cos*, J_{TP} the total rotational moment of inertia around the propeller axis, *m* the mass of the quadcopter, *g* the acceleration due to gravity, I_{XX}, I_{YY}, I_{ZZ} the body moment of inertia, and *p*, *q*, *r* the angular velocities of quadcopter. Meanwhile, Ω is the algebraic sum of the propeller speeds and Ω is defined as:

$$\Omega = -\Omega_1 + \Omega_2 - \Omega_3 + \Omega_4 \tag{2}$$

The relationship between the basic movements and the thrusts and torques generated by each propeller are written in (3), as:

$$\begin{aligned} U_1 &= b(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2) \\ U_2 &= lb(-\Omega_2^2 + \Omega_4^2) \\ U_3 &= lb(-\Omega_1^2 + \Omega_3^2) \\ U_4 &= d(-\Omega_1^2 + \Omega_2^2 - \Omega_3^2 + \Omega_4^2) \end{aligned} \qquad (3)$$

With U_1 the vertical thrust, U_2 the roll torque, U_3 the pitch torque, U_4 the yaw torque, Ω_n the propeller speed, b the thrust coefficient, d the drag coefficient and l is the distance between the center of quadcopter and the center of the propeller.

B. Experimental Data Acquisition

The developed quadcopter used in this experiment has a 60 cm span dimension with a 1.2 kg in weight. The quadcopter is operated by a human pilot through a Radio Control (RC) system and using an open source Flight Control Unit (FCU), an Ardupilot 2.5., as the main controller system. As the main controller system, the Ardupilot 2.5 is consists of a microcontroller, a gyroscope, an accelerometer and a barometer as an Inertial Measurement Unit (IMU). Four T-Motor 940 KV-BLDC combined with T-Motor 18A Electronic speed controller (ESC) and 12"x5" propellers carbon placed at its four corners of the quadcopter are used as the actuator, and a Lippo battery with a voltage regulator are used for electric supply system.

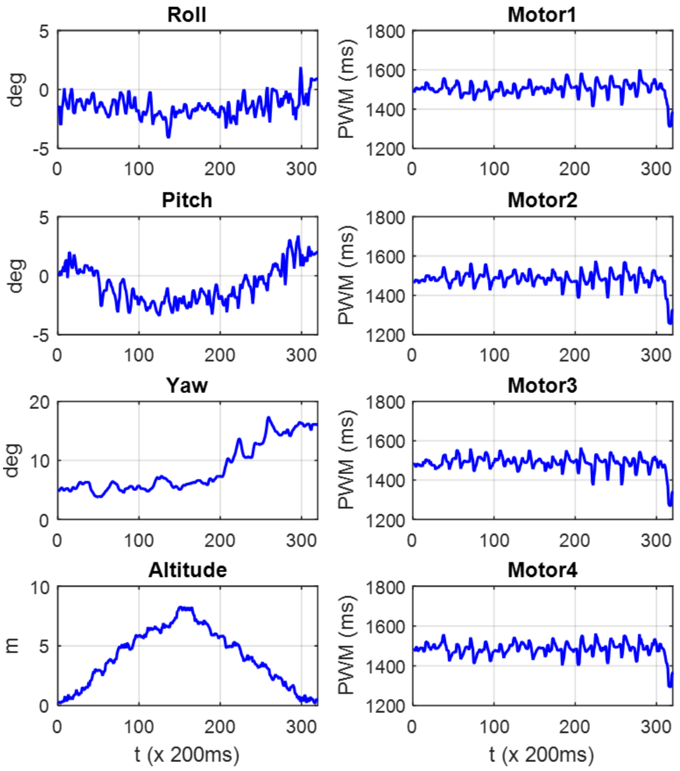
The experimental flight dataset is recorded 4 times (Fig. 2), by saving the data in the on-board memory of the flight controller, where the three of them are used as the training dataset, and the other one is used as the test dataset. As can be seen in this figure, the first and second datasets represent the steady hovering state of the quadcopter while the third and fourth data sets represent the variation of rolling and pitching maneuver around the steady hovering point.

In this experiment, the training datasets consists of the second, the third and the fourth data sets, while the first dataset is used to test the neural networks based controller system.

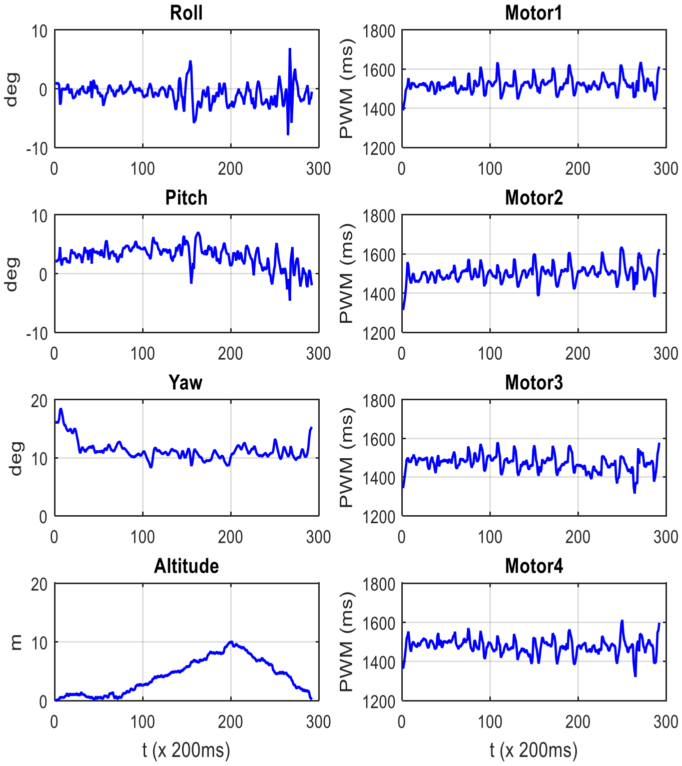
3. NEURAL NETWORK BASED DIRECT INVERSE CONTROL SYSTEM

A. Control Strategy Design

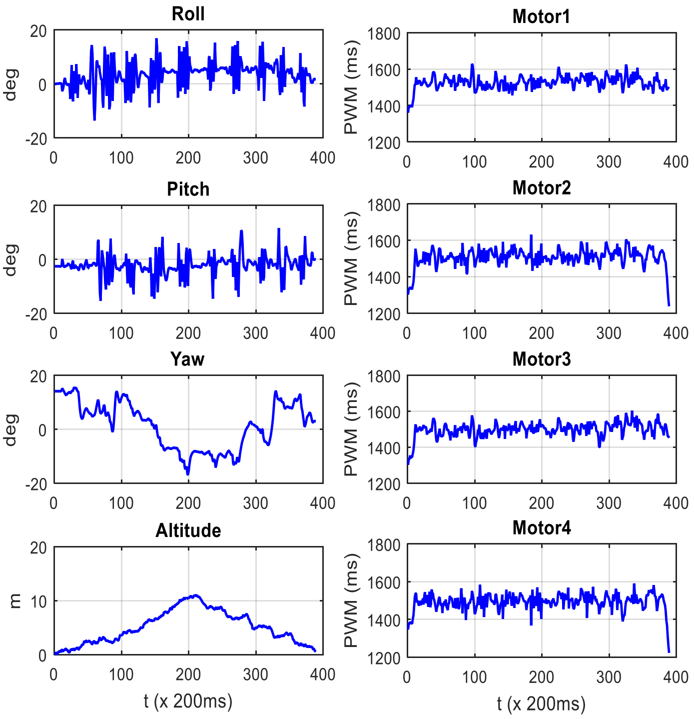
The quadcopter is an under-actuated system, because there are six state variables (X, Y, Z, ϕ, θ, ψ) of the quadcopter states should be controlled by only four input control signals, i.e., U_1, U_2, U_3, U_4, respectively. As can be clearly seen from (1) and (3), the four input signal controls produced four outputs with only U_1 that contain the value for controlling the position x, y, z, with U_2, U_3, U_4 produced the attitude and orientation of the quadcopter. Therefore, control strategy for the under-actuated system of the quadcopter is done by dividing the control system into two subsystems, as seen in Fig. 3. The inner loop control subsystem is then used for controlling the attitude movement, i.e., the roll, the pitch and the yaw, as the main part of the quadcopter control system. While the outer loop control subsystem is used for the controlling the lateral movement of the quadcopter position[8,9,10].



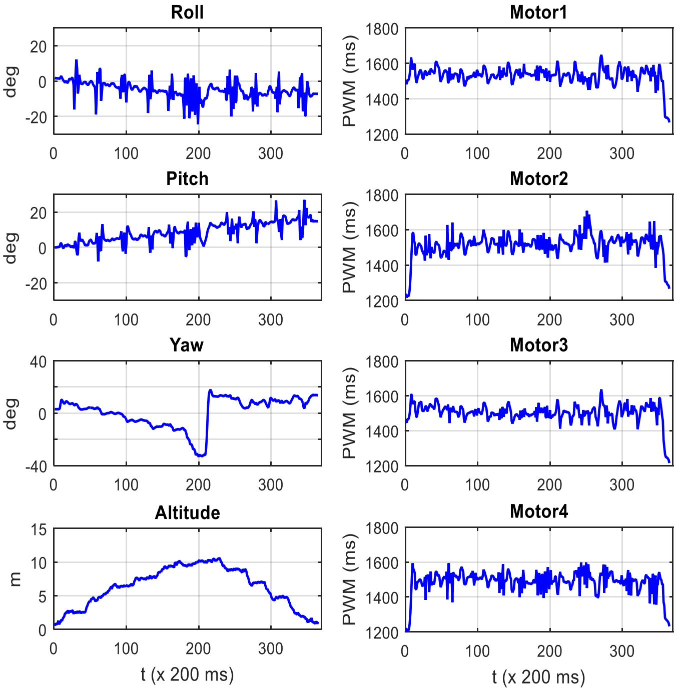
(a) Steady hovering data set as the test dataset.



(b) Steady hovering data set as the training dataset.



(c) Hovering state data set with variation of rolling and pitching as the training dataset.



(d) Maneuver data set around the steady hovering as the training dataset.

Fig. 2. The data set

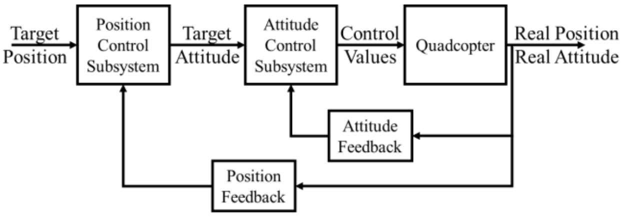


Fig. 3. Full control of quadcopter

B. DIC Strategy Design

Direct Inverse Control (DIC) is a simple strategy to implement and control nonlinear dynamics[11]. The basic idea of Direct Inverse Control (DIC) scheme is to train a neural network as the inverse of the nonlinear system of the plant in order to nullify its dynamics characteristics. The neural networks based inverse system is then utilized as the controller of the system in a cascade structure as can be seen in Fig. 4.

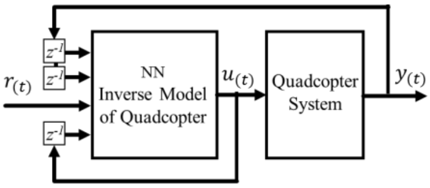
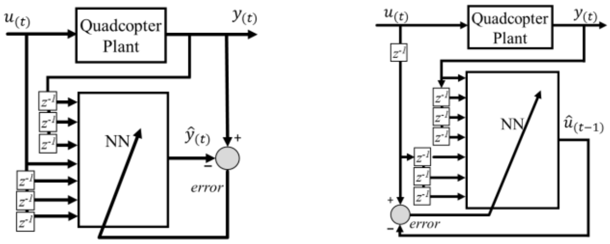


Fig. 4. Direct Inverse Control

DIC method is divided into two sections, namely (1) the system identification, and (2) an inverse model. Both of these two subsystems are trained using a back propagation learning method with an appropriate number of layers and neurons. The learning mechanism of the back propagation method is accomplished by using the system's real data to find the appropriate weights of the learning data set, and calculating the output neurons. The neural network's outputs are compared with the real target output of the training data, and the errors are used to update the neuron weights. This mechanism is done iteratively until a minimum error value is obtained.

The utilization of the DIC scheme in our quadcopter is conducted by firstly gathering the input-output data of the plant that comprise all of the operating range of the system. As can be seen from (1) and (2), the input-output dataset for our quadcopter are the input control signal $u(t)$ as the speed of rotation of each rotor, and the quadcopter flight dynamics ($X, Y, Z, \phi, \theta, \psi$) as an output signal $y(t)$.

Training the neural networks for the system identification is conducted as shown in Figure 5a, while the architectural configuration for training the neural networks based inverse model is shown in Figure 5b. The neural networks based of the system identification consists of an input layer with 28 input neurons, a hidden layer with 30 neurons and an output layer with 4 output neurons. As same as neural networks based of the system identification, an architectural configuration of neural networks based inverse model has 28 input neurons, 30 hidden neurons and 4 output neurons.



(a) Identification system (b) Inverse model

Fig. 5. Training configuration

4 EXPERIMENTAL RESULT

Training stage of the neural network based system identification has been converged at 20000 epochs with a Mean Sum Square Error (MSSE) of 2.9706. Meanwhile, the neural network training for the inverse model converged at 6000 epochs with MSSE 2888.723. The weights obtained from the training are then used as the neural-network based DIC system (Fig. 4), and tested by using the testing dataset.

Figure 6 shows the comparison of the altitude condition of the quadcopter between the real test dataset and the simulation result, while Fig. 7 shows the attitude condition of the real dataset and the simulation result using a neural networks based inverse model, both using the NN based DIC scheme.

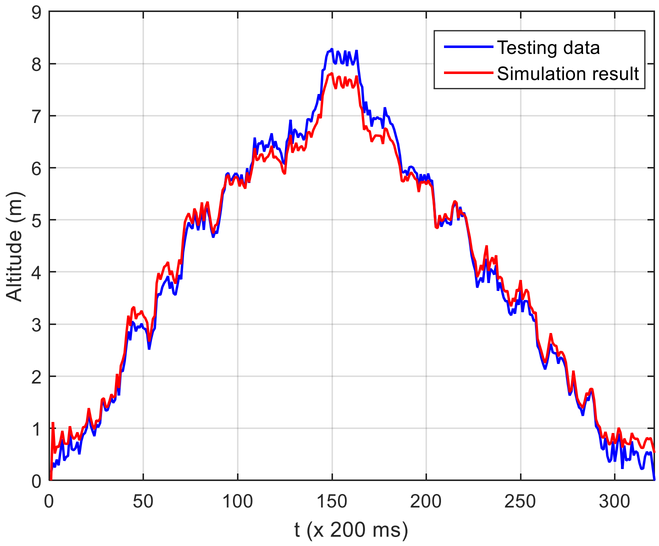


Fig. 6. Response result of altitude

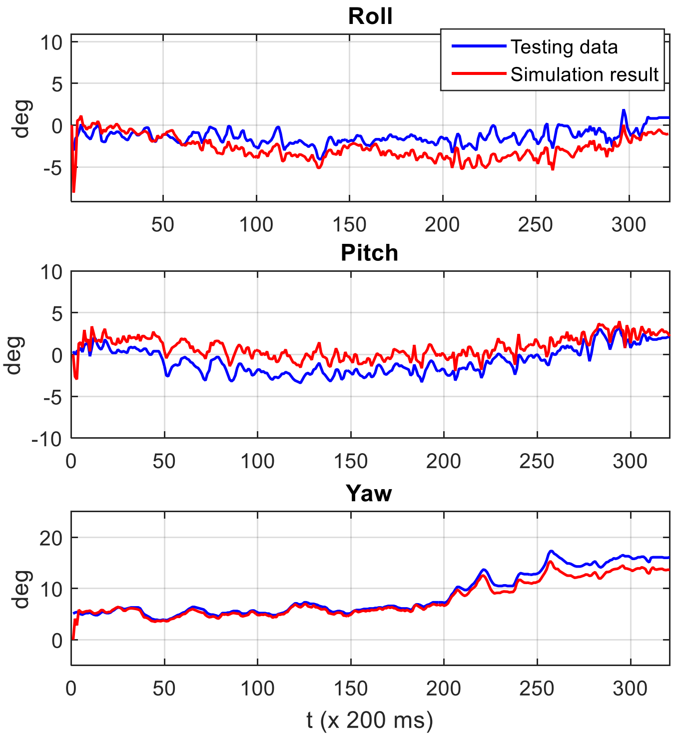


Fig. 7 Response result of attitude

As can be seen clearly in the Fig. 6, the simulation result shows that the quadcopter movement can followed the desired trajectory and maintained the hovering state with an altitude Mean Square Error (MSE) of 0.02842 meter. As also depicted in Fig 7, the MSSE of the attitude condition of the quadcopter along its course is 1.2486 degree. The low MSE and MSSE results show that the NN based DIC system has a good performance despite the existence of low errors of the altitude, and on the roll and the pitch parameters.

5 CONCLUSIONS

In this paper, we have proposed the utilization of backpropagation control system using Direct Inverse Control scheme for attitude and altitude control of a UAV quadcopter on hovering state. Real flight data experiments have proven that the proposed method can control both the attitude and altitude of the UAV with reasonable errors of *1.2486* degree and *0.02842 m*, respectively. It is therefore shown that this method can also perform well in controlling the altitude of a UAV.

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