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Design of an Adaptive-Neural Network Attitude Controller of a Satellite using Reaction Wheels

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Abstract

In this paper, an adaptive attitude control algorithm is developed based on neural network for a satellite using four reaction wheels in a tetrahedron configuration. Then, an attitude control based on feedback linearization control is designed and uncertainties in the moment of inertia matrix and disturbances torque have been considered. In order to eliminate the effect of these uncertainties, a multilayer neural network with back-propagation law is designed. In this structure, the parameters of the moment of inertia matrix and external disturbances are estimated and used in feedback linearization control law. Finally, the performance of the designed attitude controller is investigated by several simulations.

Keywords: Attitude Control, Adaptive-neural network control, Satellite, Reaction wheel.

1. Introduction

A spacecraft requires several subsystems to achieve its mission successfully. Attitude determination and control system (ADCS) is one of the most crucial subsystems of a spacecraft. The major tasks of attitude control system are to provide the capability of high maneuverability, high pointing stability and attitude accuracy for the satellite. This subsystem has different parts including, sensors, actuators, control algorithm and electronic control board. The control algorithm is an important part of ADCS that provides commands for actuators.

Difficult problems in the design of control algorithm for such a complex dynamic system are due to the inherent nonlinearities of the model because of large angle maneuvers, uncertainties and unknown environmental disturbances.

Among the research that has been done recently, there are a number of techniques that can deal with the control problems of such a complex dynamic system from classical PID control to adaptive control e.g. optimal control [1, 2, 3], sliding mode control [4], adaptive control [5, 6, 7, 8], robust control [9, 10] such as variable structure control (VSC) which are designed based on Euler angle errors or quaternion error vector.

Generally, thrusters [11] are used for quick and large angle maneuvers and reaction wheels are used for slow and high precision maneuvers. Three reaction wheels, with each one's rotational axis parallel to one of the satellite's body axes, make up the simplest control system [12]. As the three body axes' dynamics are separated, the design can be carried out independently for each axis. However, if one of the assemblies becomes damaged then the satellite's attitude can no longer be adequately controlled. For this reason, a fourth RWA is installed in order to increase the reliability of the entire system. The additional wheel is installed with its axis off the three principal axes, enabling torque control about any of those axes. Thus, the incapacity of any of the RWAs aligned with the satellite's principal axes can be compensated by the torque capabilities of the fourth wheel. In this paper, four reaction wheels in a tetrahedron configuration as satellite actuator have been considered in such a way that all four wheels have the ability to create torque control around all the axes.

In recent years, the use of intelligent systems such as neural networks, fuzzy systems, fuzzy- neural network systems, etc. to estimate variables and parameters of the system is increased. A lot of work has been performed to estimate system's states by the neural network. However, little attention has been given to the estimation of the unknown parameters of the system using neural network. In [13], a Hopfield neural network is designed to estimate the unknown parameters of the nonlinear system of an aircraft. The method employed was based on the linearization of the system and was implemented for the systems with simple dynamics. In [14], a Hopfield neural network is used to estimate the unknown parameters of a robotic arm but estimation error percentage is significant.

In this paper, an adaptive-neural network attitude control algorithm is developed using four reaction wheels in a tetrahedron configuration with uncertainties in the moment of inertia matrix and disturbance torques. In this algorithm, a simple idea to estimate unknown parameters of a satellite is used based on multilayer neural network. The neural network is the inverse of system dynamics, so that the states of the system are used as input to the neural network and the control torque is estimated by the network. In this structure, the unknown parameters are used instead of neural network's weights and by using error back propagation update law; unknown parameters converge to their true values. In addition, feedback linearization control is used to attitude control of the satellite.

2. Dynamics and Kinematics of satellite

For mathematical modeling, we suppose spacecraft as a rigid body. The general equation to describe the attitude motion of a rigid body in space (Euler equations) in the presence of momentum exchange devices (e.g., reaction wheels) is described as follows [15]:

$$\frac{dh}{dt_i} = \frac{dh}{dt_B} + \omega \times h = \dot{h}_B + \omega \times h + \dot{h}_w + \omega \times h_w \tag{1}$$

Where ω is angular velocity of spacecraft with respect to body reference frame. The angular momentum of the entire system (h) will be divided by the angular momentum of the spacecraft (h_B) and the angular momentum of the reaction wheel (h_w). The terms dh/dt_i and dh/dt_B represent the time derivative of angular momentum with respect to the inertia reference frame and the body reference frame, respectively. In equation (1) $h = I \times \omega$, where I represents the moment of inertia matrix with respect to body reference frame. By replacing $h_W = I_W \times \omega_W$ and assuming that XB, YB, ZB are the principal axes of inertia, the final equations are obtained as follow:

$$\begin{aligned} M_x &= I_x\dot{\omega}_x + \omega_y\omega_z(I_z - I_y) + I_W(\omega_y\omega_{Wz} - \omega_z\omega_{Wy}) \\ M_y &= I_y\dot{\omega}_y + \omega_x\omega_z(I_x - I_z) + I_W(\omega_z\omega_{Wx} - \omega_x\omega_{Wz}) \\ M_z &= I_z\dot{\omega}_z + \omega_y\omega_y(I_y - I_x) + I_W(\omega_x\omega_{Wy} - \omega_y\omega_{Wx}) \end{aligned} \tag{2}$$

The angular velocity of spacecraft in orbit can be expressed as follows:

$$\left[\omega_B^I\right]^B = \left[\omega_B^{OR}\right]^B + \left[\omega_{OR}^I\right]^B \tag{3}$$

Where $\left[\omega_B^I\right]^B$ is angular velocity of satellite with respect to the inertia reference frame, $\left[\omega_B^{OR}\right]^B$ is angular velocity of spacecraft with respect to the orbital reference frame and $\left[\omega_{OR}^I\right]^B$ is angular velocity of orbital reference frame respect to the inertia reference frame that all the vectors are described in the body reference frame.

When we choose the order of axes transformation as $\psi \to \theta \to \phi$ (with axes order of rotation $3 \to 2 \to 1$), where ψ, θ, ϕ are the Euler angles, the kinematics equations of the systems can be expressed as follows:

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin(\phi)\tan(\theta) & \cos(\phi)\tan(\theta) \\ 0 & \cos(\phi) & -\sin(\phi) \\ 0 & \dfrac{\sin(\phi)}{\cos(\theta)} & \dfrac{\cos(\phi)}{\cos(\theta)} \end{bmatrix} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} - \omega_0 \begin{bmatrix} \dfrac{\sin(\psi)}{\cos(\theta)} \\ \cos(\psi) \\ \tan(\theta)\sin(\psi) \end{bmatrix} \tag{4}$$

3. Reaction wheels arrangement

To provide high roll and pitch control torque as well as high speed slew capability, we consider a rigid spacecraft model with a set of four reaction wheels which are arranged in a pyramid configuration about the spacecraft yaw axis as shown in Fig. 1.

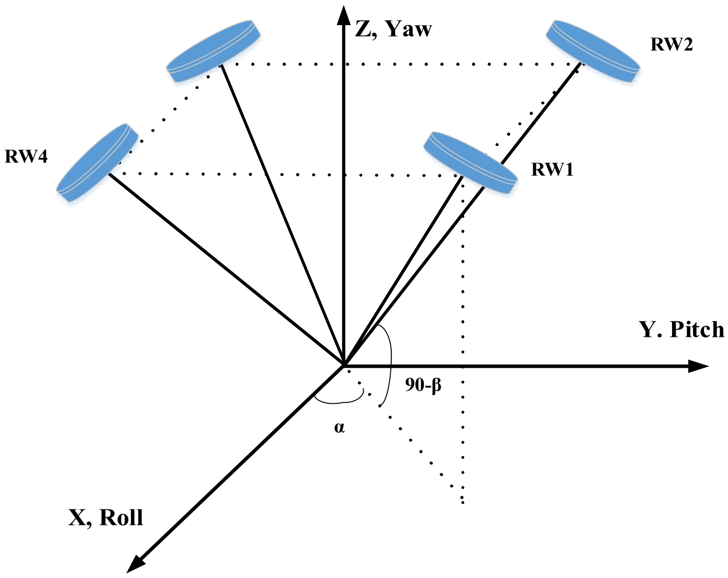

Fig. 1. Arrangement of reaction wheels

The wheel control torque vector can define as follow:

$$\dot{h}_W = \begin{bmatrix} \dot{h}_{Wx} & \dot{h}_{Wy} & \dot{h}_{Wz} \end{bmatrix} = C\dot{h}_a \tag{5}$$

where matrix (C) is the orientation matrix of the four-wheel pyramid configuration and $\dot{h}_a$ is torques generated by the reaction wheels. The orientation matrix represented by a 3 × 4 matrix (C) which is considered as follows:

$$C = \begin{bmatrix} \cos\alpha\sin\beta & -\sin\alpha\sin\beta & -\cos\alpha\sin\beta & \sin\alpha\sin\beta \\ \sin\alpha\sin\beta & \cos\alpha\sin\beta & -\sin\alpha\sin\beta & -\cos\alpha\sin\beta \\ \cos\beta & \cos\beta & \cos\beta & \cos\beta \end{bmatrix} \tag{6}$$

where C_i's (i = 1, 2, 3, 4) are the wheel axial vectors and α and β are considered as $\alpha = 45^\circ$ and $\beta = 54.74^\circ$. The energy cost by the four-wheel pyramid configuration as is shown in Fig. 1. is the smallest [16].

4. Adaptive-neural network control design

For the design of adaptive-neural network control, first the feedback linearization controller is designed and then a neural network is used to estimate the system's uncertainty.

4.1 Feedback linearization control design

For feedback linearization design, we choose the states equal to $P = \lfloor \theta_x \quad \theta_y \quad \theta_z \rfloor$ which denote the integration of the angular velocities. We choose the control moment as follows:

$$T_c = I(\ddot{P}_d - K_1\dot{\tilde{P}} - K_0\tilde{P} - \begin{bmatrix} \omega_y\omega_z(I_y - I_z) \\ \omega_x\omega_z(I_z - I_x) \\ \omega_y\omega_y(I_x - I_y) \end{bmatrix} - I_W \begin{bmatrix} \omega_z\omega_{Wy} - \omega_y\omega_{Wz} \\ \omega_x\omega_{Wz} - \omega_z\omega_{Wx} \\ \omega_y\omega_{Wx} - \omega_x\omega_{Wy} \end{bmatrix} - \begin{bmatrix} T_{dx} \\ T_{dy} \\ T_{dz} \end{bmatrix} \tag{7}$$

where, $K_1 = 2\lambda I$ and $K_0 = \lambda^2 I$ are the coefficient matrices for the desired dynamic model of controlled system and λ is a positive constant. By placing the control law in the dynamics of the system, the system dynamic error is zero (eq. (8)). That means the exponential stability is guaranteed.

$$\ddot{\tilde{P}} + 2\lambda\dot{\tilde{P}} + \lambda^2\tilde{P} = 0 \tag{8}$$

4.2 Neural network design

To estimate the unknown parameters of the system, the multilayer neural network with back propagation update law is used. Simple structure and a small number of parameters to be adjusted are the main advantages of the designed neural network. As it is shown in Fig. 2, the states of the system are inputs of the network and multilayer neural network control estimates control torques of equation (9) as equation (10).

$$\begin{aligned} M_x &= I_x\dot{\omega}_x + \omega_y\omega_z(I_z - I_y) + I_W(\omega_y\omega_{Wz} - \omega_z\omega_{Wy}) - M_{dx} \\ M_y &= I_y\dot{\omega}_y + \omega_x\omega_z(I_x - I_z) + I_W(\omega_z\omega_{Wx} - \omega_x\omega_{Wz}) - M_{dy} \\ M_z &= I_z\dot{\omega}_z + \omega_y\omega_y(I_y - I_x) + I_W(\omega_x\omega_{Wy} - \omega_y\omega_{Wx}) - M_{dz} \end{aligned} \tag{9}$$

$$\begin{aligned} \overline{M}_{cx} &= W_1\dot{\omega}_x + \omega_y\omega_z(W_3 - W_2) + I_W(\omega_y\omega_{Wz} - \omega_z\omega_{Wy}) - W_4 \\ \overline{M}_{cy} &= W_2\dot{\omega}_y + \omega_x\omega_z(W_1 - W_3) + I_W(\omega_z\omega_{Wx} - \omega_x\omega_{Wz}) - W_5 \\ \overline{M}_{cz} &= W_3\dot{\omega}_z + \omega_y\omega_y(W_2 - W_1) + I_W(\omega_x\omega_{Wy} - \omega_y\omega_{Wx}) - W_6 \end{aligned} \tag{10}$$

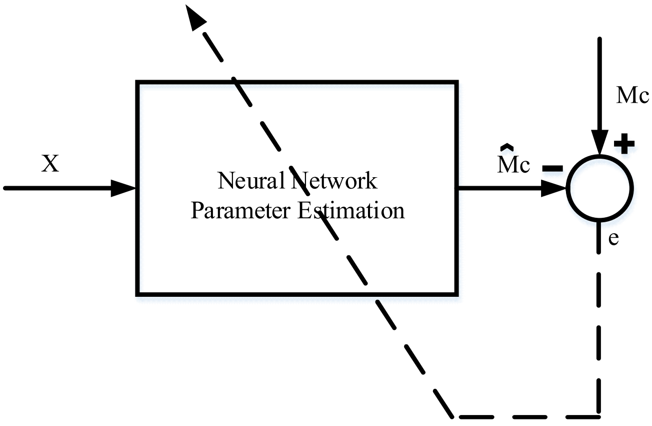

Fig. 2. Neural network diagram

In this network, the unknown parameters are considered as network’s weights, which are updated over the time and are converged to their true values. Weight updates are be done using the error between output of the network (estimated control torques) and the control torque generated by feedback linearization controller. The back propagation update law is considered as follows:

$$\Delta W = -\eta\frac{\partial J}{\partial W} = -\eta\frac{\partial J}{\partial e}\frac{\partial e}{\partial net}\frac{\partial net}{\partial W} = -ef'X = -eX \tag{11}$$

Where, J is the cost function of neural network which is defined based on the difference between the estimated torque and real torque control (equation (12)). In equation (11), f' represents derivative of activation function; f' is equal to one, since the activation function is assumed to be linear.

$$J = \frac{1}{2}e^T e \tag{12}$$

Simulation and results

In this section, to demonstrate the performance of adaptive-neural network controller and effect of uncertainty and external disturbances, the results of simulations are presented. In all simulations, desired Euler angles are considered as:

$$\psi_d = 20^\circ, \theta_d = 10^\circ, \phi_d = 10^\circ \tag{13}$$

Moreover, the satellite dynamic model, reaction wheels, controller parameters and initial conditions are summarized in Table 1. Saturation torque of reaction wheels are also considered equal to $U_m = \pm 0.7 N.m$.

Table 1. Simulation parameters

Subsystem	Parameter	Quantity
Reaction Wheels	I_W (wheel’s moment of inertia)	0.3 $Kg.m^2$
	U_m (saturation torque)	$\pm 0.7 N.m$
	α	45°
	β	54.74°
Satellite Dynamics	$\lfloor I_x \quad I_y \quad I_z \rfloor$	$[1000 \quad 500 \quad 700]\, Kg.m^2$
	$[\phi_0 \quad \theta_0 \quad \psi_0]$	$[0 \quad 0 \quad 0]$ deg
	$\lfloor \omega_{x0} \quad \omega_{y0} \quad \omega_{z0} \rfloor$	$[0 \quad 0 \quad 0]\, rad$ / sec
Adaptive Controller	K_0	1
	K_1	2

Fig. 3 to 5 show the result of simulation for roll, pitch and yaw axes respectively for adaptive-neural network attitude control of satellite. Fig. 6 shows that the tracking error for all axes is converging to zero. Fig. 7, Fig. 8. and Fig. 9 show the output torque of reaction wheels and estimation of moment of inertia and disturbances torque respectively. As it is shown in Fig. 10, since the external disturbances for all axes are considered as $M_d = 0.1\sin(t)$, the neural network estimates the unknown disturbances correctly. Fig. 11 shows the parameter estimation by a classical adaptive controller [17]. According to this figure, the controller estimates parameters in 1500 seconds; hence by using the proposed adaptive-neural network, the estimation has been decreased to 60 seconds.

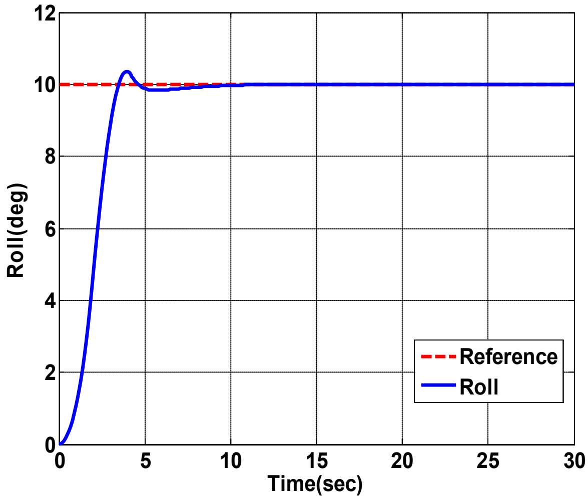

Fig. 3. Performance of adaptive- neural network for roll axis

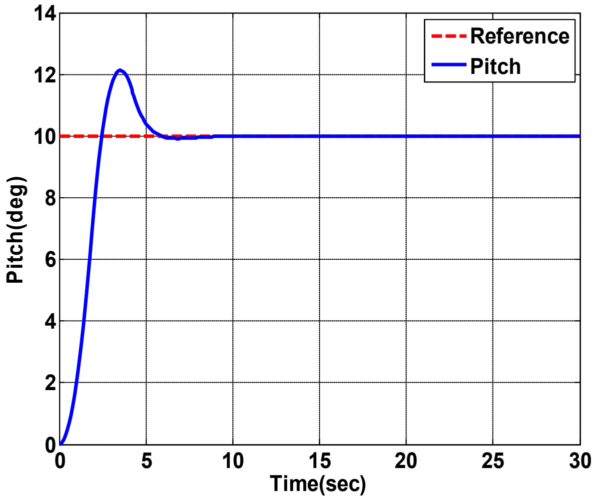

Fig. 4. Performance of adaptive- neural network for pitch axis

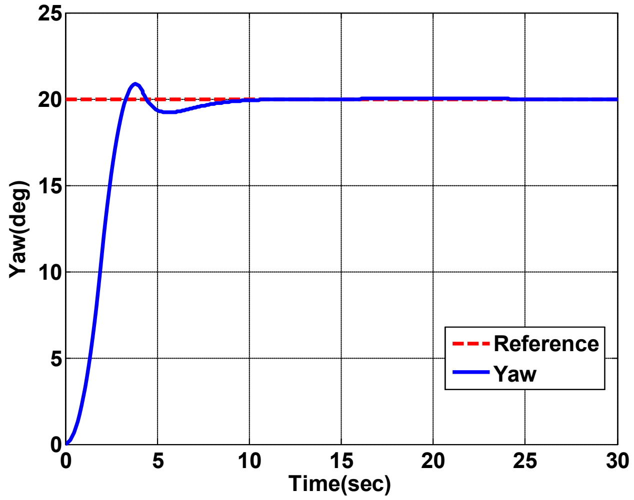

Fig. 5. Performance of adaptive- neural network for Yaw axis

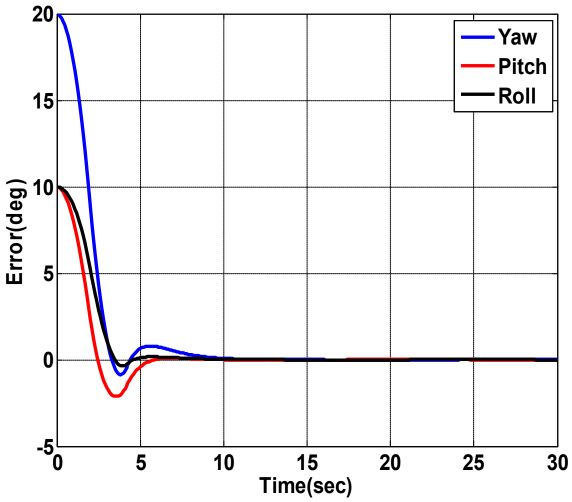

Fig. 6. Tracking error of desired Euler angles for adaptive-neural network controller

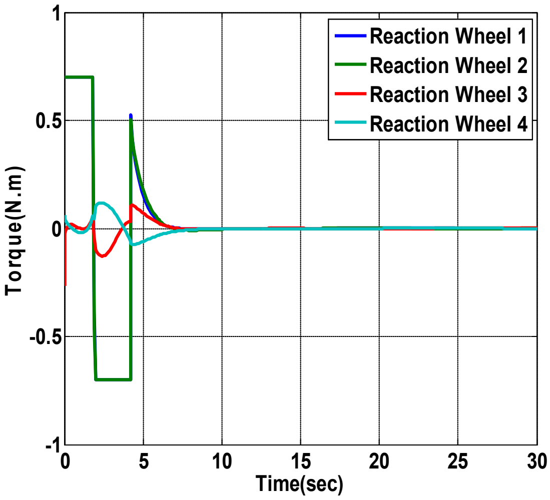

Fig. 7. Output torque of reaction wheels

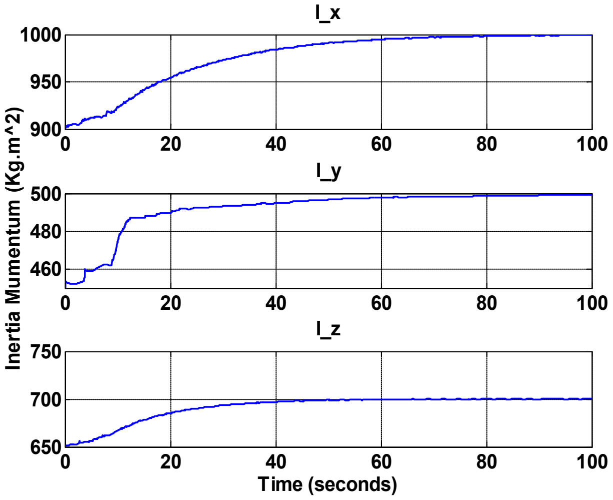

Fig. 8. Estimation of moment of inertia parameters by adaptive-neural network controller

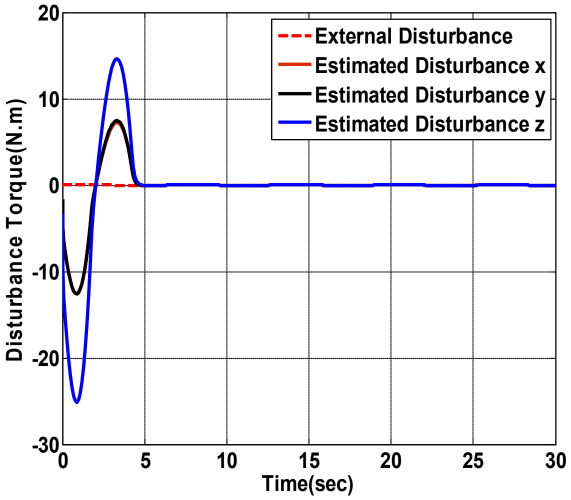

Fig. 9. Estimation of external disturbances by adaptive-neural network controller

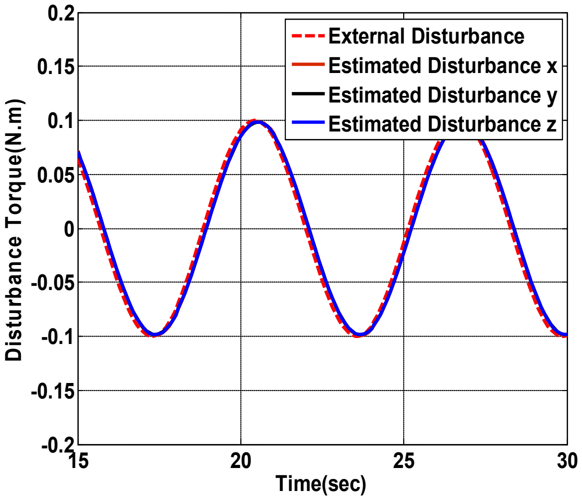

Fig. 10. Estimation of external disturbances by adaptive-neural network controller

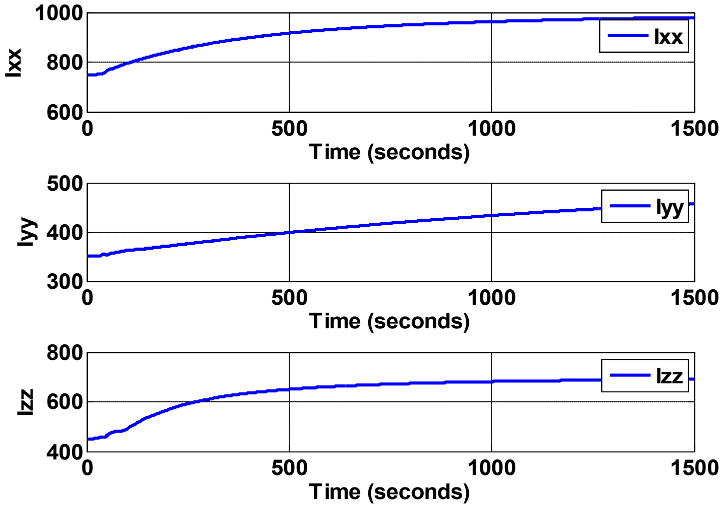

Fig. 11. Estimation of moment of inertia parameters by classical adaptive controller [17]

5. Conclusion

In this paper, an attitude control algorithm in the presence of four reaction wheels in a tetrahedron configuration as the satellite actuator was designed. Then adaptive-neural network attitude control using feedback linearization controller and multilayer neural network with back propagation update rule as a parameter estimator was designed in the presence of uncertainties in the moment of inertia matrix and disturbances torque. Results of simulation of designed attitude controller show that using the adaptive-neural network controller not only can decrease the attitude tracking error and increase accuracy of system's performance, but also estimates the unknown parameters of the system correctly.

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