Neurocontrol Design for an Aerodynamics System: Simple Backpropagation Approach

Nor Mohd Haziq Norsahperi and Kumeresan A. Danapalasingam

Abstract This paper proposes a Neurocontrol (NNC) for a Twin Rotor Aerodynamics System (TRAS) by a simple backpropagation approach to improve the pitch position accuracy. A concept known as gradient descent method is applied to adjust the weights adaptively. The approach has several notable merits namely low computational cost, simple and promising controller. The viability of NNC is verified by using MATLAB to analyze the tracking performance and control effort. PID control is benchmarked against the proposed NNC to determine the effectiveness of the controller. From the simulation work, it was discovered that NNC was superior then PID controller by reducing about 14%, 23% and 97% in the value of the overshoot, settling time and steady-state error respectively. The promising part of NNC was the improvement shown in the controller effort by significantly eliminating the fluctuation and chattering in the control signal. By looking into the future, this work will be a foundation for future improvement due to the fact that there are numerous types of approaches could be embedded in the Neural Network algorithm.

Keywords Neural network · Artificial intelligence · Nonlinear control · Twin rotors aerodynamics · Backpropagation · Gradient decent

1 Introduction

Twin Rotor Aerodynamics System (TRAS) is a bench helicopter prototype driven by two DC motors for actuating two subsystems which are horizontal (azimuth) and vertical (pitch) subsystems and TRAS inherits most of the real twin-turbine helicopters

N. M. H. Norsahperi
Department Electrical and Electronics Engineering, Faculty of Engineering, Universiti Putra Malaysia (UPM), 43400 UPM Serdang, Selangor, Malaysia
e-mail: nmhaziq@yahoo.com

K. A. Danapalasingam (✉)
Centre for Artificial Intelligence and Robotics, School of Electrical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia (UTM), 81310 UTM Skudai, Johor, Malaysia
e-mail: kumeresan@utm.my

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physical fundamental. The dual rotors offer numerous benefits due to its maneuver capability. Such criterion is worthwhile and it has a great potential to be deployed practically [1] especially for indoor and outdoor operations such as in surveillance and rescue missions. Designing a controller for TRAS is a challenging task due to its highly nonlinear nature, uncertainties and heavy cross-coupling parameters between both subsystems [2, 3] where most of the conventional controllers such as PID controller alone is inadequate in handling high order systems and TRAS's features [4]. In [5, 6], PID controller has been implemented and the findings indicate that PID control is unable to suppress the oscillation and overshoot which can be harmful to the passenger and high energy consumption [1].

Various types of artificial intelligence (AI)-based approaches have been proposed to control the complex aircraft maneuvers to augment the position accuracy of the pitch subsystem. One of the promising approaches is by embedding the artificial intelligence technique in the control strategies. The authors in [7, 8] have used bio-inspired optimization method to obtain the best PID controller's parameters, however, the oscillation and high overshoot still occur due to the nonlinearity and uncertainty features of TRAS. In view of this shortcoming, Fuzzy logic-based controls are introduced to enhance the tracking response such as type-2 [9], hybrid Fuzzy-PID [10] and Takagi-Sugeno [11] approaches. Despite such controllers offer a good performance, the controller design is complicated and the operator experience is essential in constructing the membership function.

Another potential AI approach is neural network (NN). The NN algorithm has been widely implemented in the control stream for many purposes especially in attaining the optimal controller's parameters either by self-training [12] or auto tuning [13] and as well as a control strategy [14, 15]. In [14, 15], NN control produces prominent results in a highly nonlinear system. For similar application, Feedforward NN and feedback linearization [16] and single-neuron NN [17] are designed to improve the tracking performance. Based on these findings, the transient performance of TRAS has not reached a satisfactory performance and the unwanted oscillation is not significantly reduced. From the overview, it can be deduced that there is little publication on integrating NN control for TRAS system. Hence, in this paper, a simple 3 layers NN control is proposed to improve the pitch tracking performance, reduce the oscillation and minimize the controller effort. The findings of this study will be used as a preliminary result for future development of NN control for the nonlinear system.

2 Neurocontrol

A nonlinear model to represent the pitch angular position was derived as in [18]. The moment's equation in the vertical plane was derived based on Newton's second law. Before the iterative process, the weights were randomly initialized and the learning rate was arbitrarily selected. The designed neurocontroller (NNC) processed the information from the current and the total previous error ($e(t)$ and $\int e\, dt$, respectively) as the inputs to generate the control signal ($u(t)$) by simply distributing the inputs

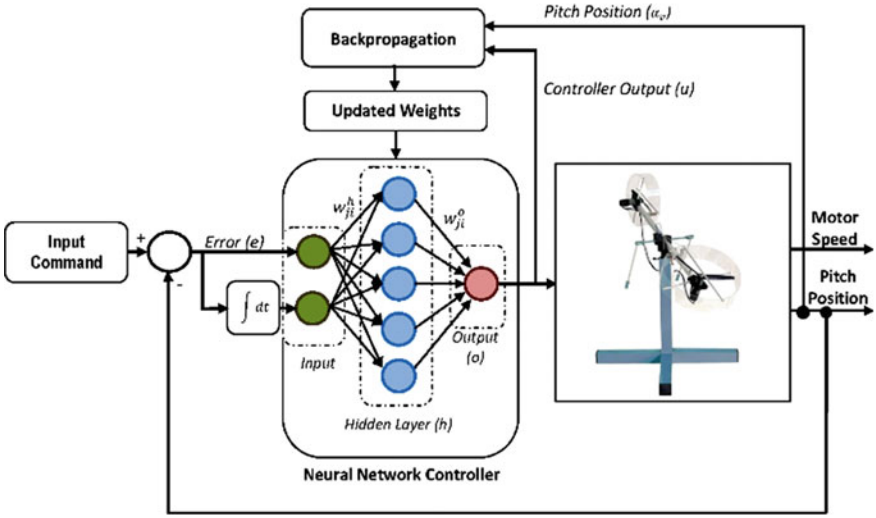

Fig. 1 System architecture with neural network control

to each neuron branches. For this work, 5 neurons in hidden layer and 1 neuron in output layer were designed as illustrated in Fig. 1 and the weights were offline tuned. The data from the pitch angle, error signal and control input were used in the learning algorithm to compute the best weight coefficients in NNC. The rectified linear unit (ReLU) was employed as the activation function in each neuron and it can be defined as

$$f(x) = \begin{cases} 0 \, for \, x < 0 \\ x \, for \, x \geq 0 \end{cases} \tag{1}$$

and x is given by

$$x = \sum_{i=1}^{n} w_{ji} o_i \tag{2}$$

where o_i is the output from each neuron. In order to adjust the weight (w_{ji}^h and w_{ji}^o), the iterative process of gradient descent method was used in minimizing the error function in weight space and each weight increment can be described by

$$\Delta w_{ji}(t) = \Delta w_{ji}(t-1) + \frac{\partial J}{\partial e} \frac{\partial e}{\partial y} \frac{\partial y}{\partial u} \frac{\partial u}{\partial w_{ji}} \tag{3}$$

and the gradient descent can be simplified by

$$\frac{\partial J}{\partial e} = \frac{\partial}{\partial e}\frac{1}{2}e(t)^2 = e(t) \tag{4}$$

$$\frac{\partial e}{\partial y} = \frac{\partial}{\partial y}\left(y_d(t) - y(t)\right) = -1 \tag{5}$$

$$\frac{\partial y}{\partial u} = sign\left(\frac{dy}{dt}\cdot\frac{dt}{du}\right) \tag{6}$$

$$\frac{\partial u}{\partial w_{ji}} = \left(\frac{\partial u}{\partial w_{11}^h}, \frac{\partial u}{\partial w_{12}^h}, \frac{\partial u}{\partial w_{11}^o}, \frac{\partial u}{\partial w_{12}^o}, \ldots\ldots, \frac{\partial u}{\partial w_{ji}^o}, \frac{\partial u}{\partial w_{ji}^h}\right) \tag{7}$$

where, $y_d(t)$ and $y(t)$ are the desired and actual output respectively. Then, the new weights were computed by total increment

$$w_{ji}(t) = w_{ji}(t-1) - \eta\Delta w_{ji}(t) \tag{8}$$

where, η(between [0,1]) is the learning rate to determining the convergence speed.

3 Simulation Results

This section summarizes the findings when NNC was implemented on the TRAS model. The NNC controller performance was compared with the PID controller [19], to observe the performance paradigm. Figure 2 illustrates the TRAS response when both controllers were implemented and the square-wave input was exerted.

Based on Fig. 2, the overshoot (os) was reduced by 14% and practically, such distortion reduction is significant especially when the system is utilized in the restricted space and for a comfort ride. The settling time (t_s) and the steady-state error (e_{ss}) were reduced by 23% and 97%, respectively. These results translate the capability of NNC in delivering an accurate positioning. Despite the improvement of several

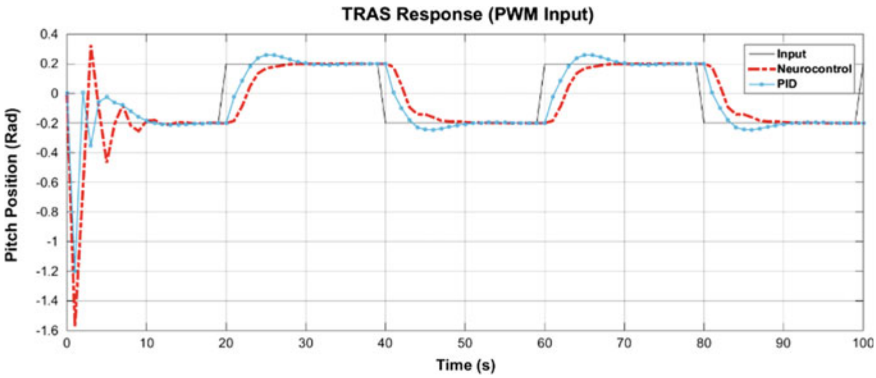

Fig. 2 Square-wave input response for SISO pitch position control

Table 1 Comparison of controller responses

Controller	t_r (s)	t_s (s)	os (%)	e_{ss} (rad)	MSE
PID [19]	2.47	9.34	14.73	0.0295	0.0224
NNC	2.72	7.19	0.41	0.0008	0.0423

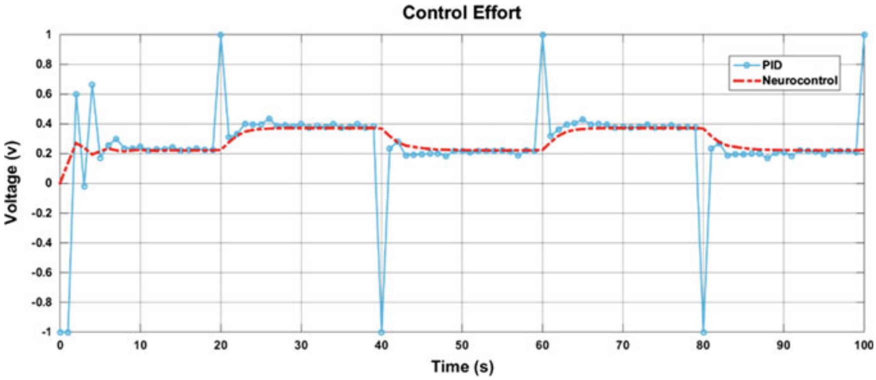

Fig. 3 Controller effort of squared-wave input response

features, there was an augment in the mean square error (MSE) and the rise time (t_r) but this value has no significant effect on the overall performance as the increment was almost unseen. Table 1 summarizes the controller performance characteristics.

One unanticipated finding was the reduction of the controller effort, considering the fact that NNC was designed for the position accuracy and overshoot reduction. Figure 3 illustrates the controller effort of NNC and PID controllers where the fluctuation feature was suppressed when NNC was applied on TRAS. This is an encouraging result as in practical control system, minimizing the control effort is desirable as it could reduce the hardware cost, energy consumption and heat dissipation which is agreed by authors in [20].

4 Conclusion

This study was undertaken to design and evaluate NNC capability in delivering an accurate pitch positioning for TRAS by using simple backpropagation method. The investigation has concluded that the position accuracy and distortion reduction could be obtained by using NNC in the highly nonlinear system. The second major finding is NNC could minimize the controller effort while sustaining the desired performance by filtering the excessive signal during the signal transmission. Further research might explore the selection of NNC input and the modification of the NN algorithm in order to reduce the tracking error and improve the robustness of such controller.

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