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Intelligent adaptive nonlinear flight control for a high performance aircraft with neural networks

Aydogan Savran,[a,*] Ramazan Tasaltin,[b,†] Yasar Becerikli[c,‡]

[a]*Department of Electrical and Electronics Engineering, Faculty of Engineering, Ege University, Bornova, İzmir 35100, Turkey*
[b]*Department of Electrical and Computer Engineering, College of Engineering, King Abdul Aziz University, Jeddah 21413, Saudi Arabia*
[c]*Department of Computer Engineering, Faculty of Engineering, Kocaeli University, Kocaeli 41040, Turkey*

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Abstract

This paper describes the development of a neural network (NN) based adaptive flight control system for a high performance aircraft. The main contribution of this work is that the proposed control system is able to compensate the system uncertainties, adapt to the changes in flight conditions, and accommodate the system failures. The underlying study can be considered in two phases. The objective of the first phase is to model the dynamic behavior of a nonlinear F-16 model using NNs. Therefore a NN-based adaptive identification model is developed for three angular rates of the aircraft. An on-line training procedure is developed to adapt the changes in the system dynamics and improve the identification accuracy. In this procedure, a first-in first-out stack is used to store a certain history of the input-output data. The training is performed over the whole data in the stack at every stage. To speed up the convergence rate and enhance the accuracy for achieving the on-line learning, the Levenberg-Marquardt optimization method with a trust region approach is adapted to train the NNs. The objective of the second phase is to develop intelligent flight controllers. A NN-based adaptive PID control scheme that is composed of an emulator NN, an estimator NN, and a discrete time PID controller is developed. The emulator NN is used to calculate the system Jacobian required to train the estimator NN. The estimator NN, which is trained on-line by propagating the output error through the emulator, is used to adjust the PID gains. The NN-based adaptive PID control system is applied to control three angular rates of the nonlinear F-16 model. The body-axis pitch, roll, and yaw rates are fed back via the PID controllers to the elevator, aileron, and rudder actuators, respectively. The resulting control system has learning, adaptation, and fault-tolerant abilities. It avoids the storage and interpolation requirements for the too many controller parameters of a typical flight control system. Performance of the control system is successfully tested by performing several six-degrees-of-freedom nonlinear simulations.

Keywords: Intelligent; Identification; Flight control; Neural network; Levenberg-Marquardt; Adaptive PID

1. Introduction

Aircraft dynamics are in general nonlinear, time varying, and uncertain. Traditionally, flight control systems are designed by using the mathematical model of the aircraft linearized at various flight conditions [1]. The aircraft motion variables are sensed and fed into the aircraft control surface actuators via some feedback gains. The adjustment process of the feedback gains according to the flight condition is called gain scheduling. Since controller designs are performed off-line using a limited number of linearized and time-invariant

*E-mail address: aydogan.savran@ege.edu.tr
†E-mail address: rtasaltin@yahoo.com
‡Corresponding author. Tel.: +90 262 3351168. Fax: +90 262 3351150. E-mail address: becer@kou.edu.tr, ybecer@ieee.org

models, extensive gain scheduling computation is required. While this approach may handle mild nonlinearities, it is not suitable for highly nonlinear problems. The gain scheduling approach may produce a control law that exhibits the desired properties around the design points locally but not globally [2]. As aircrafts have become more complex, traditional methods have not yielded acceptable performance [3]. To overcome these problems, nonlinear control techniques such as feedback linearization are studied as alternatives to gain scheduling [4]. These techniques are difficult to use because they rely heavily on accurate knowledge of aircraft dynamics [5]. However, some aerodynamic effects are very difficult to model resulting in uncertainties in the aircraft dynamics. In this paper, we propose a neural network (NN) based on-line identification model that can compensate these uncertainties.

A totally different approach to the flight control is to use the NN technology. Neural networks (NNs) have powerful mapping capacity, learning property, and parallel implementation paradigm. Since NNs have the ability to approximate uncertain nonlinear mappings to a high degree of accuracy [6], they are proposed for identification and control of nonlinear dynamic systems in many investigations [7–12]. In recent years, neural networks have widely appeared in flight control researches. Neural network based control laws have been designed for a longitudinal control system [13], a lateral-directional control system [14], autopilot systems [15], control augmentation systems [4], stability augmentation systems [16], restructurable flight control systems [17], a reconfigurable flight control system [5], and helicopter flight control systems [18,19]. Although these studies give good results, some either invoke special simplifications or linearizations related to the aircraft model, not encompassing the full nonlinear six-degrees-of-freedom (6DOF) aircraft dynamics.

In this paper, a more comprehensive approach is proposed. NN-based dynamic modeling and intelligent controller schemes for a high performance aircraft are developed without simplifications or linearizations in the aircraft dynamics. The learning, adaptation, and fault-tolerant abilities of the intelligent flight control system are demonstrated using a nonlinear F-16 aircraft model. All of the control surfaces of the aircraft model are controlled by the developed controllers. The NN based flight control designs are considered in two phases.

The objective of the first phase is to model the dynamic behavior of the F-16 aircraft with NNs. A dynamic identification model is developed for three angular rate variables of the aircraft model using serial-parallel identification structure and nonlinear function approximation ability of the NNs. Initially, the NN based identification model is trained off-line using the input-output data of the system. Since the off-line trained model is insufficient to compensate system uncertainties, an on-line training procedure is proposed. One way of on-line training is to use one pattern for each time step. But, if only one pattern at each time step is used, the NN weights will be driven to minimize the sum of the squared error for that pattern alone. To improve the complete mapping, the training is performed using more patterns. This is achieved by using a first-in first-out stack to store a short history of the training patterns similar to the windowing done in digital signal processing [20]. In our approach, the stack discards the oldest pattern from it and accepts a new pattern from the system at each time step. The batch learning is performed over all patterns in the stack at each time step using the Levenberg-Marquardt (LM) method with the trust region approach. So, an adaptive NN based identification model is obtained to model aircraft dynamics that have nonlinearities and uncertainties. It can be used to develop adaptive, fault-tolerant flight controllers.

The second phase deals with developing intelligent flight controllers. Therefore a NN based adaptive PID control scheme is developed. In this scheme, the learning and adaptation abilities of the NN are combined with the robust performance of the PID controller. The control system is composed of an emulator NN, an estimator NN and a discrete time PID controller. The emulator NN is trained as a forward model of the plant and used to calculate the system Jacobian. It is trained off-line using prior knowledge and then trained on-line by means of the stack previously mentioned. The estimator NN is used to adjust the PID gains. The LM method is used to train both NNs. The control system has learning, adaptation, and fault-tolerant abilities. So, it can adapt to the changes in flight conditions and system parameters and can accommodate the system failures. It is used to control