Engineering Applications of Artificial Intelligence 74 (2018) 322–335

Contents lists available at ScienceDirect

Engineering Applications of Artificial Intelligence

journal homepage: www.elsevier.com/locate/engappai

Neural network based adaptive control of airplane's lateral-directional motion during final approach phase of landing

Mihai Lungu *, Romulus Lungu

University of Craiova, Faculty of Electrical Engineering, 107 Decebal Blvd., Craiova, Romania

ARTICLE INFO

Keywords:
Adaptive control
Neural network
Landing
Dynamic inversion
Reference model

ABSTRACT

The paper presents three new autonomous systems for the control of lateral-directional motion of airplane during landing. The geometry of airplane motion in lateral-directional plane takes into account the wind having different velocities and directions. All the three control systems contain an adaptive control subsystem based on the concepts of dynamic inversion and neural networks; the reference models of the adaptive control systems receive the signals provided by Pseudo Control Hedging blocks, as additional signals, to cancel the neural networks' adapting difficulties in the case of nonlinear actuators with time delay and saturation zones with respect to the velocity and displacement. Two of the three automatic control systems have proportional–derivative/proportional–integral– derivative controllers for the control of the lateral deviation of airplane with respect to the runway. The new designed adaptive architectures have been software implemented and validated by complex numerical simulations; the obtained results prove the new architectures' stability and small overshoots.

1. Introduction

There are many methods to design automatic control systems and automatic landing systems (ALSs); for the control of the lateral motion during landing, an Instrumental Landing System (ILS) type radio-navigation system together with a system used for the obtaining of distances between the airplane and the runway radio-markers (Sereewattana et al., 2015) can be used. The direction controllers (used within such ALSs) are proportional–derivative (PD) type, proportional–integral (PI) type, proportional–integral–derivative (PID) type, in classical of fuzzy variants (Zhi and Yong, 2012; Lungu et al., 2013, 2011). Other structures of ALSs use optimal controllers consisting of state observers (Nugroho, 2014). Also, for airplane trajectory's control during landing, the usage of optimal control laws $\left(H_2,\ H_\infty,\ H_2/H_\infty\right)$, together with full- or reduced-order observers, provide good results (Huang et al., 2017; Yazici and Sever, 2016; Tong et al., 2011). For a safety landing, the required information in lateral-directional plane is obtained by means of gyro transducers, accelerometers, or radio-technical transducers whether or not the landing control architecture includes an observer.

The usage of different adaptive control architectures such as the ones based on the dynamic inversion technique and neural networks (NNs), with or without Pseudo Control Hedging (PCH) blocks (Swei and Nguyen, 2014; Zhang and Holzapfel, 2015; Calise et al., 2006) is motivated by the presence of known nonlinearities associated to the dynamics of airplane or actuators as well as external disturbances. Generally, the dynamic inversion is based on the philosophy of feedback linearization, the plant nonlinearities being canceled and the closed loop plant behaving like a stable linear system; the method is characterized by simplicity in the control structure, ease of implementation, global exponential stability of the tracking error etc (Singh and Padhi, 2009). The general theories of the dynamic inversion technique, classical/fuzzy dynamic compensators, neural networks, and PCH blocks (Zhang and Holzapfel, 2015; Calise et al., 2006; Baur et al., 2011; Abe et al., 2016; Lungu and Lungu, 2016a; Calise et al., 2000) can be extended to the design of new architectures of ALS. The adaptive component of the control law has to compensate the approximation error of the nonlinear component for airplane and actuator dynamics. The PCH blocks are introduced when the actuators are nonlinear, this affecting the neural networks; the NNs are sensitive to actuator nonlinearities, while the PCH blocks eliminate their adapting difficulties; the advantage of the neural networks is their approximation ability, the NNs being capable to approximate an unknown system dynamics through learning. Generally, the PCH blocks "move back" the reference models, introducing correction responses of the reference models with respect to the estimation of the execution element's position. The signals provided by PCH blocks are additional inputs of the reference models (Zhang and Holzapfel, 2015;

---

* Corresponding author.
E-mail addresses: Lma1312@yahoo.com (M. Lungu), romulus_lungu@yahoo.com (R. Lungu).

https://doi.org/10.1016/j.engappai.2018.07.006
Received 5 April 2017; Received in revised form 20 October 2017; Accepted 16 July 2018

Baur et al., 2011); thus, the actuators' saturation zones are avoided. Such automatic landing systems are slower than others but are characterized by much smaller overshoots and stationary errors.

The complexity and uncertainties in modeling the aerodynamic phenomena (uncertainties regarding the modification of flight parameters and dynamics), as well as the strongly nonlinear character of the actuators (expressed primarily by the presence of the nonlinearities with the saturation zone) are the main reasons leading to the need of adaptive control laws. Thus, because the atmospheric conditions and the dynamics of aircraft are drastically changing during flight and, of course, during landing, it is difficult to land safely by using conventional controllers. Using the above concepts, the present paper presents three new adaptive architectures for airplane control in lateral-directional plane during final approach stage of landing; this study was motivated by the fact that, according to the authors of the present paper, little progress has been reported in the design of the landing flight control systems in lateral-directional plane by using neural networks, the dynamic inversion concept, linear dynamic compensators, state observers, and PCH blocks. Also, it is interesting to see if airplane trajectory during final approach (lateral-directional plane) can be tracked with high enough accuracy by neural network based controllers using both the dynamic inversion technique and PCH blocks. The present work is the continuation of the studies in Lungu and Lungu (2016a), where an adaptive landing architecture for airplane control in lateral-directional plane has been designed and software implemented. There are many differences between the ALS designed in Lungu and Lungu (2016a) and the ones proposed here: (1) the ALS in Lungu and Lungu (2016a) uses a direction controller, while here the three ALSs have controllers for the lateral deviation of airplane with respect to runway (Y); (2) the architecture in Lungu and Lungu (2016a) uses a glide slope and direction radio-technical system, while the ALSs in our paper use a calculation block for airplanes' horizontal coordinates; this way, the three new auto-landing control systems allow setting the wind velocity and direction, increasing thus the systems' robustness; (3) the architecture in Lungu and Lungu (2016a) controls the difference between the direction of the runway and the airplane flight direction $\left(\Delta\psi = \psi - \overline{\psi}\right)$, while the new ALSs in this paper control the airplane's flight direction (ψ), the lateral acceleration of airplane $\left(a_y\right)$, and airplane's yaw angular rate (r), respectively; (4) beside different outputs, the ALS in Lungu and Lungu (2016a) uses, as feedback signal, the deviation of airplane's longitudinal axis with respect to runway direction (λ), while the ALSs in this work use the signals provided by the calculation block for airplane's horizontal coordinates. Moreover, in this paper, different order reference models (first-, second-, and three-order) are used for obtaining the desired values of variables that must be controlled. Taking into account the advantages of the elements and techniques used in this paper (NNs, dynamic inversion, PCH blocks) and the fact that, till now, only one paper (Lungu and Lungu, 2016a) deals with the control of aircraft, during final approach phase of landing (lateral-directional plane) by means of neural networks, dynamic inversion concept, linear dynamic compensators, state observers and PCH blocks, the present paper contains absolute novelties in the search area of ALSs' design.

In Wagner and Valasek (2007) some feed-forward neural networks based on the back propagation learning algorithm have been used, but their main disadvantage is related to the priori training on normal and faulty operating data. Other approaches which involve time delay neural networks are characterized by insufficient flight path track accuracy and limited operating conditions (Karacor et al., 2011; Chen et al., 2013; Juang and Cheng, 2006; Braff et al., 1996). The main disadvantages of the NN based approaches designed in Karacor et al. (2011) and Chen et al. (2013) are the required operating conditions which are not easy to satisfy in practical control applications. A learning technique using network or networks with back-propagation through time algorithms has been designed in Juang and Cheng (2006), the main drawbacks of the method being related to: (1) the number of hidden units determined by trial; (2) the high convergence time. The auto-landing systems designed in the above mentioned works are characterized by insufficient generality or accuracy and, therefore, the aim of the paper is to develop a control system that can handle different climatic conditions; for this, neural network and dynamic inversion based control systems could be a good choice.

The paper is organized as follows: the geometry of airplane's motion in horizontal plane, taking into account the lateral wind, is given in the second section; the three new ALSs are presented in the third section of the paper, while the design of these new adaptive systems for the control of airplane's motion in lateral-directional plane during the final approach phase of landing is given in the fourth section; in the next section, complex simulations to validate the new designed ALSs have been performed and the obtained results are analyzed; finally, some conclusions are shared in the sixth section of the paper.

2. Geometry of airplane landing in lateral-directional plane

In Fig. 1.a there are presented the parameters associated to airplane's motion in horizontal (lateral-directional) plane $O\xi\eta\zeta$ ($O\xi$ – tangent to the locus's parallel and East oriented, $O\eta$ – tangent to the locus's meridian and North oriented); $\vec{V}$ and $\vec{V}_v$ are the airplane's velocity and the wind velocity, having the directions Ψ and Ψ_v the axis OX is the direction of the runway, oriented under the angle $\overline{\psi}$ with respect to the axis $O\eta$, while the axis OY is the lateral axis – perpendicular to the axis OX; OX and OY are situated in the horizontal plane $O\xi\eta$. The initial position of airplane with respect to the two horizontal coordinates' frames can be expressed by means of the coordinates X_0, Y_0 and ξ_0, η_0, respectively. The impact point between the airplane and the runway is T, having the coordinates $(X, 0)$ and $\left(\xi_T, \eta_T\right)$, respectively. The distance covered by airplane along the OX axis until the cancel of the lateral deviation Y_0 is $\left(X - X_0\right)$. The tangent to the trajectory of airplane intersects the OX axis in the point P_2. The distance $\overline{P_1P_2}$ is $k\left(X - X_0\right)$, where k is a positive constant; each value of k corresponds to a flight trajectory. The resultant velocity $\vec{V}_{rez} = \vec{V} + \vec{V}_v$ is tangent to this trajectory and has the components $\dot{X}$ and $\dot{Y}$. Projecting $\vec{V}_{rez}$ on the axes OX and OY, one obtains the equations:

$$\begin{aligned} \dot{X} &= V\cos\left(\overline{\psi} - \psi\right) + V_v\cos\left(\overline{\psi} - \psi_v\right), \\ \dot{Y} &= V\sin\left(\overline{\psi} - \psi\right) + V_v\sin\left(\overline{\psi} - \psi_v\right). \end{aligned} \tag{1}$$

In order to obtain the airplane's cinematic trajectory $(Y = f(X))$, the equations are integrated if the time evolution of $\psi(t)$ is known. The yaw angular rate $r(t) = \dot{\psi}(t)$ is considered the command variable for the system (1), having the states $X(t)$ and $Y(t)$. To obtain such control law, similar triangles for the velocities and coordinates are used; it results:

$$\frac{\dot{X}}{\dot{Y}} = \frac{k\left(X - X_0\right)}{Y}. \tag{2}$$

Considering $E = Y\dot{X} - k\left(X - X_0\right)\dot{Y}$ — the error for the accomplishment of Eq. (2), in order to have $E \to 0$, one chooses the proportional control law (Lungu et al., 2011):

$$\dot{\psi}_c(t) = k_R\left[Y\dot{X} - k\left(X - X_0\right)\dot{Y}\right],\ k_R > 0; \tag{3}$$

$\dot{\psi}_c$ is the calculated value of the yaw angular rate.

If airplane's control during the final approach stage (horizontal plane) is achieved with respect to the lateral deviation Y (Fig. 1.b), the angular deviation (λ) and the direction deviation $\left(\Delta\psi \equiv \overline{\psi} - \psi\right)$ must simultaneously tend to zero;

$$\sin\lambda \cong \lambda = \frac{Y}{R},\ \sin\Delta\psi \cong \Delta\psi = \frac{\dot{Y}}{V_0}, \tag{4}$$

with λ and $\Delta\psi$ — measured in radian, R — the distance between airplane and the runway's end point, while V_0 is the resultant velocity at moment t_0 (the start of the turn maneuver). The conditions $\lambda \to 0$ and $\Delta\psi \to 0$ are simultaneously met if $Y \to 0$ and $\dot{Y} \to 0$. This can be achieved by using a PD controller, with the transfer function $\frac{\varphi_c(s)}{\Delta Y(s)} = k_y^{\varphi} + k_y^{\dot{\varphi}}s$; is the airplane's roll angle, while φ_c — is the calculated value of this angle.