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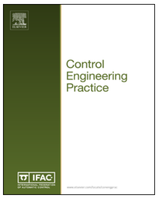

Robust auto-landing of fixed-wing UAVs using neuro-adaptive design

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ABSTRACT

An innovative neuro-adaptive design philosophy is presented in this paper embedding a Sobolev norm based Lyapunov function for directional learning of the unknown function, which is capable of learning both the unknown function in the system model and its Jacobian. This facilitates fast learning (model adaptation) without much of transient effects. The updated model is then used in the framework of dynamic inversion to design the guidance (outer) loop as well as the control (inner) loop. Using this philosophy a robust adaptive nonlinear guidance and control design is presented for robust automatic landing. The performance of the proposed approach is successfully verified through numerous simulation studies using the six degrees-of-freedom (six-DOF) nonlinear model of a prototype UAV. All possible disturbance effects that arise in practice, namely modeling inaccuracies, wind disturbances and ground effect, have been considered in the simulation studies.

1. Introduction

Unmanned missions with different levels of autonomy and intelligence are into every application domain ranging from large to miniatured vehicles. UAVs that are used for deploying weapons, reconnaissance, surveillance, coastal security and other hazardous tasks have to be robust to operate in any environment. Environment for the operation of UAV may be unmodeled or vary with unknown external disturbances. However, UAVs that are designed to operate in such unfavorable conditions require to be rugged, which may otherwise result for either lost of aircraft or failure of mission. Historically, most of the aircraft accidents were occurred during landing in unfavorable approach conditions which might occur either due to wind disturbances or unexpected aerodynamic response because of ground effect. Safety of UAV is at most critical for repeated missions which either takeoff or land very often. Thus, although equipping a UAV with the ability to perform automatic landing increases the complexity of the system, it does have the potential to render a more versatile UAV and also to reduce the long term costs and risks involved in landing phase of missions.

Most serious aircraft accidents have been caused by aircraft encountering abrupt wind shear while attempting to take off or land. Shear is present during almost every takeoff and landing but it can be so slight that it gets compensated without even realizing its presence. If the same shear is strong enough, then vehicle cannot penetrate safely for which it needs to be designed for robust landing. Moreover, low altitude flight demands for quick counteractive action to avoid loss of control. Simulation study using an appropriate engineering mathematical model of wind disturbance shall provide to explore innovative means to quickly respond to disturbance as in actual scenario. Often in aircraft model simulation development, shear and gust effects of the atmosphere are neglected. Meteorological circulations or terrain-induce airflows can on occasion induce large and rapidly changing variations in air velocity over small distance. These variations produce corresponding sudden changes in the relative flow of air over the aircraft's wings and other lifting surfaces, with attendant changes in the aircraft actual flight path. Tailwinds or headwinds may not be of major concern as any substantial loss of time can be compensated by varying thrust. Vertical and lateral wind are principal sources expected to cause significant flight deviation. Moreover, during final flare phase of landing, air flow over the wing is modified due to ground effect. This can even alter the longitudinal stability of vehicle at that critical phase which is difficult to control even by an experienced pilot.

Automatic landing problem, with these numerous challenges and complexities, has invoked interest among various researchers. Various auto-landing architectures are developed based on selection of either decoupled linear model or nonlinear six-DOF model of aircraft. Aircraft landing procedure has three defined phases as initial approach, glide and flare (Parkinson, O'Connor, and Fitzgibbon, 1996; Prasad and Pradeep, 2007). Linear control theory has

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been heavily investigated. Modern control methods like H_2/H_∞ have also been used for landing of UAVs (Shue, Agarwal, and Kuo, 1998; Wang and Shen, 2007). Dynamic inversion is a popular method of nonlinear control which relies on the philosophy of feedback linearization (Enns, Bugajski, Hendrick, and Stein, 1994; Slotine and Li, 1991). The automatic landing controller in Singh and Padhi (2009) was designed based on Nonlinear Dynamic Inversion, which tracks the predefined path through all three phases of landing. The dynamic inversion has also been used for the design of longitudinal auto-landing (Ha and Choi, 2002) and for the control of micro-aerial vehicles (Smith, Swei, and Tischler, 2004). This feedback control structure cancels the nonlinearities in the plant such that the closed loop plant behaves like a stable linear system. This method has several advantages like simplicity in the control structure, ease of implementation, good exponential stability of the tracking error. The robustness with nonlinear control had also been studied and reported (Lavergne, Villaume, Jeanneau, Tarbouriech, and Garcia, 2005; Sadraey and Colgren, 2006). There is a need to increase the robustness of controller due to parameter variation. Design and implementation of robust guidance and control algorithms is one of the key elements in the development of reliable UAV systems. Several approaches to this problem have been proposed including robust linear control, neural network, and fuzzy control. Uncertainties during flight that are caused by exogenous disturbances need to have robust controllers like H_∞. Che and Chen (2001) implemented H_∞ and stable inversion to achieve robust tracking in the presence of wind shear and gust. Neural networks are also applied in auto-landing system by Miller, Sutton, and Webros (1992) and Saini and Balakrishnan (1997).

Wind shear during landing has been a topic of extensive research since it is identified as a major contributor for many aircraft accidents. Availability of mathematical model for wind and advanced measuring instruments made it possible to estimate the wind behavior. Incorporating the temporal and spatial gradient terms of wind shear into 6 DOF nonlinear model and its influence on the aerodynamic coefficients is well addressed by Frost and Bowles (1984). The presence of wind shear can occur from a variety of sources, atmospheric factors like microbursts and geographical factors like wake effects of building near ports. In addition to wind shear, turbulence that refers to irregular and disturbed flow in atmosphere produces gusts and eddies. Continuous gusts are modeled as random processes which lasts for several minutes of flight. Robust nonlinear H_∞ controller is used for automatic landing of UAV in the presence of wind gust (Yang, Garratt, and Pota, 2012). The two most widely used models of continuous gusts are the Dryden and von Karman models (Airworthiness Standards, 2011; MIL-HDBK-1797, 1997). Assumptions in these continuous gust model are well described in Etkin (2005), and the same are assessed in Hoblit (1988) to get an adequate model for simulation.

Parameter uncertainty during flight especially at low altitude provide little space for it to respond back. Moreover, during flare phase ground effect can significantly influence the longitudinal stability of an aircraft. This problem may even get more worse if cross wind prevails during landing. Hence, ground effect poses a challenging problem during landing. Staufenbiel and Schlichting (1988) made in-depth study on stability of airplane in ground effect. Impact of ground proximity on static and dynamic stabilities of aircraft are well explained by designing a simple controller for flare maneuver. Knowledge of aerodynamic parameters in ground proximity helps in better design of controller for aircraft during landing. Trend in variation of longitudinal derivatives with height is shown in Boschetti, Cardenas, Amerio, and Arevalo (2010). Drella and Youngren (2006) used to compute these parameters that are affected during ground effect by method of images for the aircraft configuration. Stability of vehicle during ground effect has concerns mainly in longitudinal direction and it can be avoided if the controller is fast enough to model these uncertainties.

With all these, the autonomous landing requires an intelligent path planning and guidance. Under uncertainty, MRAC is widely used for control of aircraft. Because of strong nonlinearities of aerodynamic characteristics and imperfect wind model, neural networks can be used to model these uncertainties. Modeling these nonlinearities require fast and error free adaptation. In particular, during landing under wind disturbance structure of uncertainty is not clear for which neural network is the best adaptive element to model such nonlinear uncertainties. Hence, neuro-adaptive control with nonlinear dynamic inversion as a base line controller is used here for automatic landing.

In this paper, philosophy of neuro-adaptive control from Padhi, Unnikrishnan, and Balakrishnan (2007) is used. The proposed technique is completely non-iterative and it required only evaluation of closed form formulas for weight learning, function evaluation and control computation. Gaussian RBF based neural network is used for modeling the uncertainty and disturbance. Neural network weight update rule is derived using Lyapunov theory, which guarantees both stability of the error dynamics and boundedness of the weights of network. For the UAV model used, variation of aerodynamic derivatives that are affected in the presence of ground proximity is approximately calculated using AVL. Trend in the variation of derivatives is shown which explains the dominance of ground effect on UAV during landing.

Two neuro-adaptive controllers are used: one in guidance loop and another in control loop. In guidance loop, translational kinematic equations are used to track the approach phase based on the path planned. In the presence of unknown wind disturbance, there exists certain uncertainty in these translational kinematic equations which is adaptively modeled using first neuro-adaptive control. Desired attitude and forward velocity of UAV thus obtained from guidance loop are fed to control loop which has another neural network to model the parameter uncertainty in rotational dynamic equations that creep because of variation of aerodynamic derivatives.

The remainder of the paper is organized as follows. In Section 2, neuro-adaptive controller architecture is detailed for which nonlinear dynamic inversion is selected as a base line nominal controller. It also includes the derivation of Sobolev norm based Lyapunov stable learning algorithm. In Section 3, six-DOF nonlinear model of aircraft without and with wind shear terms is detailed, followed with wind gust model. In the same section, ground effect on UAV is explained with the trend in variation of derivatives. Then in Section 4, complete implementation of neuro-adaptive auto-landing from path planning, guidance and to control is detailed. Simulations based on this auto-landing architecture are discussed in Section 5. Results and plots for various cases like microburst, ground effect and other combinations of wind shear and gust are shown here.

2. Dynamic inversion based neuro-adaptive controller

2.1. Nonlinear dynamic inversion

Consider a nonlinear dynamical system which is affine in control and given by

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}) + \mathbf{G}(\mathbf{x})\mathbf{u}, \quad \mathbf{x}(\mathbf{0}) = \mathbf{x_0}$$

$$\mathbf{y} = \mathbf{h}(\mathbf{x})$$

where $\mathbf{x} \in \mathbf{R^n}$, $\mathbf{u} \in \mathbf{R^m}$, $\mathbf{y} \in \mathbf{R^p}$ are the state, control and output vectors of nominal system respectively. For a bounded, smoothly varying signal $\mathbf{y}_*$, a control $\mathbf{u}$ need to be designed such that $\mathbf{y}$

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