Design and Validation of an $\mathcal{L}_1$ Adaptive Controller for Mini-UAV Autopilot

Elisa Capello · Giorgio Guglieri · Fulvia Quagliotti · Daniele Sartori

Received: 7 May 2012 / Accepted: 12 July 2012 / Published online: 4 August 2012
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Abstract The dynamics of Unmanned Aerial Vehicles (UAVs) is nonlinear and subject to external disturbances. The scope of this paper is the test of an $\mathcal{L}_1$ adaptive controller as autopilot inner loop controller candidate. The selected controller is based on piecewise constant adaptive laws and is applied to a mini-UAV. Navigation outer loop parameters are regulated via PID control. The main contribution of this paper is to demonstrate that the proposed control design can stabilize the nonlinear system, even if the controller parameters are selected starting from a decoupled linear model. The main advantages of this technique are: (1) the controller can be implemented for both linear and nonlinear systems without parameter adjustment or tuning procedure, (2) the controller is robust to unmodeled dynamics and parameter model uncertainties. The design scheme of a customized autopilot is illustrated and different configurations (in terms of mass, inertia and airspeed variations) are analyzed to validate the presented approach.

Keywords UAVs · Adaptive controller · Autopilot design

1 Introduction

Unmanned Aerial Vehicles (UAVs) represent an ideal platform for testing advanced control techniques. In recent years, many researches regarding the design of UAV autopilot algorithms using modern control theories have been completed. Most of the modern autopilots incorporate controller algorithms to meet the always more demanding requirements of flight maneuvers and mission accomplishment. However, due to the complexity and the computational need of the control algorithms, most of the commercial autopilots are based on Proportional Derivative Integrative (PID) philosophy. The scope of the present research paper is the implementation of an adaptive controller that is robust in presence of model uncertainties due to platform geometric and inertial variations which occur during the flight tests (such as variations on payload mass). The simple structure, the reduced presence of...
oscillations during the implementation and a minimum computation effort make the $L_1$ adaptive controller the ideal candidate for an autopilot control law. Two cases are analyzed: (1) a linear decoupled state space model for a specific flight condition and (2) a nonlinear model obtained from the complete equations of motion. In both cases a two loop controller is implemented. The inner loop is synthesized using an $L_1$ adaptive algorithm for pitch, roll and airspeed control; the outer loop instead is based on PIDs to control altitude and heading.

As explained in [1], different and advanced control techniques have been implemented in autopilot systems to guarantee the desired performance. Most commercial autopilots are based on PID controllers because they are easy to tune and to understand. Moreover, by using PIDs the designers have a good control of the system dynamics. In detail, starting with proportional gain and adding integral and derivative terms, the designers can obtain a zero steady state error for a step input and a fast time response. Many methods for PID tuning can be found in literature, [2] and [3] provide a good review of different robust and optimal techniques. In the last years, some researchers have focused the attention on the development of automatic tuning and adaptation techniques for the definition of the PID gains. For example, [4] have proposed a computationally efficient procedure for $H_{\infty}$ PID optimal design instead of brute force search. The method proposed in Ho’s paper revealed important structural properties of $H_{\infty}$ PID controllers. Authors of [5] have proposed a set of simple closed formulas for the explicit computation of the parameters in finite terms. They eliminate graphical, heuristic and trial and error procedures to verify the robustness of the selected parameters. The main drawback of PID autopilot is its lack of adaptivity due to the changes in the UAV dynamics. This means that the PID parameters need to be retuned in the presence of wind disturbances or in case the payload characteristics are changed. For this reason adaptive controllers could be a good candidate for the control of autonomous UAV flight.

A variety of adaptive control techniques have been proposed for the derivation of autopilot inner loops. Researchers in [6] implemented a two-loop controller where the inner loop is a dynamic inversion controller with an adaptive neural network and the outer loop is a LQR controller. Similarly, [7] presented the implementation of an adaptive neural network controller for autonomous flight. However, traditional model-based adaptive controllers may not be applicable since they are generally useful on the condition that the system dynamics are linear-in-the-parameters. In [8] the authors presented an alternative adaptive controller based on neural networks using backstepping technique. The main feature of [8] is that the adaptive controller is designed assuming that all of the nonlinear functions of the system have uncertainties and the neural network weights are adjusted adaptively via Lyapunov theory. Similarly, [9] derived an adaptive backstepping approach for the longitudinal aircraft control and a Lyapunov analysis of the stability properties of the closed loop system was considered. Paper [10] extended the case presented by [9] including the control of the roll channel. As explained in the previous references, even if Lyapunov techniques assure the convergence of the tracking error and low computational effort is required, they do not necessarily ensure parameter convergence. The authors of [11] proposed an $L_1$ adaptive pitch controller for a mini UAV and validated the proposed algorithm in experimental flight tests. The $L_1$ adaptive control methodology addresses some of the problems exhibited by traditional adaptive control approaches by providing fast and robust adaptation, simultaneously leading to desired transient performance for the system input and output signals, in addition to steady-state tracking. The decoupling between fast adaptation and robustness is achieved via the introduction of a low-pass filter on the adaptive control signal. This key element can be based on robustness and performance specifications. The complete theory is presented in [12, 13]. A drawback of [11] is the implementation and validation of a single loop (a pitch attitude hold).

Compared with the existing results previously discussed, a contribution of the present paper is the validation of the controller parameters when a nonlinear complete aircraft model is considered (both longitudinal and latero-directional planes), including model uncertainties and unmodeled