



Contents lists available at ScienceDirect

Annual Reviews in Control

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

Full Length Article

A longitudinal flight control law to accommodate sensor loss in the RECONFIGURE benchmark

J.M. Maciejowski*, E.N. Hartley, K. Siauyls

University of Cambridge Department of Engineering, Trumpington Street, Cambridge, CB2 1PZ, United Kingdom

ARTICLE INFO

Article history:

Received 8 December 2015

Revised 12 May 2016

Accepted 1 June 2016

Available online xxx

Keywords:

Optimal control

Robust control

Aircraft control

Aerospace

Fault-tolerant control

Flight envelope protection

ABSTRACT

The feedback gains in state-of-the-art flight control laws for commercial aircraft are scheduled as a function of values such as airspeed, mass, and centre of gravity (CoG). If measurements or estimates of these are lost due to multiple simultaneous sensor failures, the pilot must revert to an alternative control law, or, in the ultimate case, directly command control surface positions. This work develops a robust backup load-factor tracking control law, that does not depend on these parameters, based on application of theory from robust MPC and H_2 optimal control. Firstly, the methods are applied with loss only of airdata, and subsequently also with loss of mass and CoG estimates. Local linear analysis indicates satisfactory performance over a wide range of operating points. To keep the aircraft within an acceptable operating region, an outer protection loop is implemented using an override approach, based on ground speed, a model of the trim angle of attack and variation of load factor with respect to angle of attack, and *a priori* bounds on the wind speed. Finally, the resulting control laws are demonstrated on the nonlinear RECONFIGURE benchmark, which is derived from an Airbus high fidelity, industrially-validated simulator.

© 2016 International Federation of Automatic Control. Published by Elsevier Ltd. All rights reserved.

1. Introduction

Automatic control systems are integral to the operation of modern civil airliners (Favre, 1994), reducing the pilot's workload through stability augmentation and providing a consistent response to commands through the whole flight envelope. The open-loop response of the aircraft varies considerably, and when a linear feedback control law is used, it is usual to schedule its parameters based on the flight point. For example, when controlling the longitudinal short-period mode, load factor (n_z) and pitch rate (q) are fed-back, but the control law parameters are scheduled as a function of a combination of airspeed, altitude, Mach number, mass and centre-of-gravity of the aircraft. Each parameter used must therefore be measured or estimated.

Under some specific circumstances, erroneous flight parameters can propagate downstream to the flight control law computation, making the aircraft difficult to handle. Hardware redundancy is the typical mitigating measure (Brière, Favre, & Traverse, 1995; Goupil, 2011). To achieve robustness to sensor failure, multiple sensors can be employed and a "voting" mechanism implemented to detect and compensate for a large class of faults (Goupil, 2011). Analytical redundancy (where multiple signals are combined to reconstruct

an estimate of a parameter without explicitly measuring it) can also be exploited, providing additional fault-tolerance without the burden of additional physical hardware. However when too many simultaneous sensor faults occur, the signals must be considered as polluted and ignored.

The key purpose of this paper is not the development of new theory, but to present an approach for addressing the requirements of a challenging, industrially-motivated application. Section 2 presents an extension of an approach explored in Hartley and Maciejowski (2015), for the control of the longitudinal dynamics of a large commercial aircraft in a scenario where airspeed data is lost. Whilst relatively unusual, this scenario can emerge due to multiple simultaneous faults on air data and angle-of-attack sensors (so angle of attack cannot be used to estimate airspeed). In this situation, one recourse is to switch to a direct control law, where elevator deflection is commanded directly. However, the presented approach aims to maintain a load-factor control law with reasonable robustness and handling qualities, so as to limit the inevitable additional workload falling on the pilot. Stable operation is also subsequently demonstrated where estimates of mass and centre of gravity are lost. In contrast to Hartley and Maciejowski (2015), the control synthesis approach also considers stability of the interpolated control laws used between design points. Prior work by Puyou and Ezerzere (2012) achieved robustness to loss of flight parameter measurements through applying non-smooth optimisation to obtain a fixed-complexity

* Corresponding author.

E-mail addresses: jmm@eng.cam.ac.uk (J.M. Maciejowski), edward.hartley@cantab.net (E.N. Hartley), ks555@cam.ac.uk (K. Siauyls).

controller robust to loss of mass and centre of gravity estimates. The remaining scheduling information was introduced through an inner-loop nonlinear dynamic inversion (NDI) controller due to difficulties of interpolating dynamic systems. Similarly, Varga, Ossmann, and Joos (2014) proposed a non-scheduled backup C^* control law, tuned using multi-objective optimisation. In contrast, the presently proposed approach does not require an additional inner control loop, yet allows a load factor control law to be maintained.

Section 3 considers flight envelope protection (e.g., Falkena, Borst, Chu, & Mulder, 2011; Well, 2006). Flight envelope protection is becoming a common feature of commercial aircraft, which can automatically override the pilot (or autopilot) command to prevent the aircraft exiting the envelope within which it has been designed to operate. This type of system allows the pilot to reflexively perform full stick deflections in response to unanticipated situations without worrying about causing a stall. To protect against overspeed, under-speed, and angle-of-attack limit violations, conventionally, measurements of the airspeed and angle of attack are employed. If the integrity of the airspeed and angle of attack measurements is lost, the existing systems must be disengaged. One of the requirements specified in the RECONFIGURE Benchmark Scenario Description is to “keep the aircraft in a safe region” in the case of detected loss of angle of attack and airspeed measurements. The controller described in Section 2 does not, on its own, fulfil this requirement. A replacement flight envelope protection system is therefore proposed in Section 3, employing ground speed measurements, a model of the aerodynamic behaviour, and *a priori* bounds on the wind speed.

Section 4 presents results obtained from testing the robust inner loop controller and the outer loop flight envelope protection system in an industrial high-fidelity nonlinear simulator provided by Airbus for use in the RECONFIGURE project. Details of the simulator and the wider scope of the project can be found in Goupil et al. (2014, 2015).

2. Inner loop load factor control law

2.1. Control problem

Airbus has provided the RECONFIGURE consortium with linearisations of the longitudinal dynamics of an aircraft in straight-and-level flight at 234 different flight points. These cover an envelope of altitudes, airspeeds, masses and centre-of-gravity (CoG), with 214 of the flight points covering “clean” aerodynamic configurations with slats and flaps fully retracted, and a further 20 covering configurations with the high-lift devices extended to various degrees and landing gear also extended in some configurations. Altitudes range from 5000 ft to 35,000 ft, the ratio of maximum to minimum airspeed for a given altitude-mass-CoG combination is up to 1.6, and the highest mass is 2.15 times the lowest. The rigid-body models are accompanied by simplified linear sensor, filter and actuator models. This study considers a setup where all elevators act in common mode, and neglect the trimmable-horizontal-stabiliser (THS), which in any case can only control at much lower frequency ranges than those considered. A sampling period $T_s = 0.04$ s is used.

The objective is to control only the short-period dynamics (leaving the pilot or an outer loop to control the phugoid mode). Classically the short-period dynamics are modelled with the pitch rate q and angle-of-attack α as states, with q , α and vertical “load factor” n_z as outputs. (Strictly, the load factor is the ratio of lift to weight, however in this paper its deviation from trim (i.e., the acceleration normal to the aircraft body divided by acceleration due to gravity) is universally considered). Usually, α is not available at sufficiently high bandwidth to be used for the innermost control loop, so q and n_z are used as feedback variables. The control input

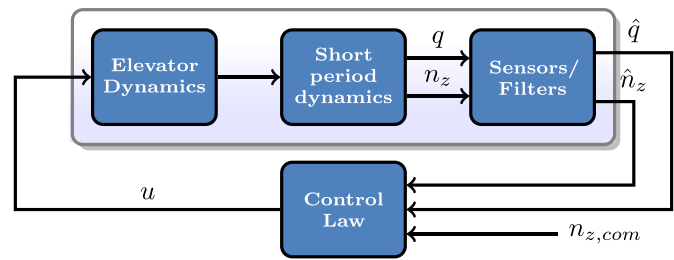


Fig. 1. Schematic of inner loop control design setup.

is the elevator deflection (multiple elevators operating in common mode). For design purposes, the short-period model at each flight point is augmented with a first-order-plus delay actuator model for the elevator and first-order low-pass linear sensor models on q and n_z , followed by a first-order low-pass filter yielding estimates $\hat{q}$ and $\hat{n}_z$ of the true values (Fig. 1). These approximate the higher-order “true” filters, which also include notches to attenuate certain structural modes. There is an implicit assumption that the existing filters are unalterable.

Let x denote the combined state vector of the elevator dynamics, short-period mode and sensors/filters and y denote the measured output $[\hat{q}, \hat{n}_z]^T$. The short-period dynamics vary with the current airspeed, altitude, CoG, and mass. The parameters that determine the flight point are denoted as ϑ . The augmented linearised plant model at a given flight point ϑ sampled at time step k , with period T_s can be described by the parameterised linear difference equations:

$$x(k+1) = A(\vartheta)x(k) + B(\vartheta)u(k) \quad (1a)$$

$$y(k) = C(\vartheta)x(k) + D(\vartheta)u(k). \quad (1b)$$

Delays in the model result in it being strictly proper, i.e. $D(\vartheta) = 0$.

The specification for the RECONFIGURE project (Goupil et al., 2014; 2015) states that the closed-loop response should have the following time-domain characteristics. First, the response to a step change in commanded n_z should be “substantially finished” within 6 s. The corresponding pitch rate q should not overshoot its steady state value by more than 30%, the load factor should not overshoot its setpoint by more than 10%, and the “control anticipation parameter” (CAP) should be “consistent” throughout the flight envelope. For an ideal second order model of the short period mode, CAP is defined as $\dot{q}(0)/n_z(\infty)$ in response to a step input. The consistency requirement reflects the importance of pitch acceleration as a cue for the pilot during changes in load factor. In addition it is desirable to have a local 60° phase margin and a 6 dB gain margin at the linear design points, although in degraded conditions, it may not be possible to achieve all of these simultaneously on top of the nominal design uncertainty.

2.2. Theoretical grounding

Let $\mathcal{I} \triangleq \{1, \dots, 234\}$ be an index for the 234 design points, and ϑ_i , for $i \in \mathcal{I}$ denote the flight parameters for the i th flight point. Define subsets of the flight points $\mathcal{J}_j \subseteq \mathcal{I}$, $j = 0, \dots, j_{\max}$, as “flight groups” such that $\mathcal{J}_m \cap \mathcal{J}_n = \emptyset$, $\forall m \neq n$, and let ϑ_{ji} denote the parameters of the flight point indexed by the i th element of $\mathcal{J}_j$. The design objective can be posed as the finding $j_{\max}$ control laws $\kappa_j(z)$ that each stabilise all flight points in $\mathcal{J}_j$, with satisfactory tracking performance. It is assumed that parameters vary slowly in comparison to the controlled dynamics and can be locally approximated as time-invariant.

Download English Version:

<https://daneshyari.com/en/article/4999567>

Download Persian Version:

<https://daneshyari.com/article/4999567>

[Daneshyari.com](https://daneshyari.com)