Engineering Applications of Artificial Intelligence 67 (2018) 368–380

Contents lists available at ScienceDirect

Engineering Applications of Artificial Intelligence

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

Proof of concept simulator demonstration of a physics based self-preserving flight envelope protection algorithm

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ARTICLE INFO

Keywords:
Aircraft control
Flight envelopes
Fault-Tolerant systems
Self-Preserving systems
Physical models
Adaptive algorithms

ABSTRACT

This article discusses the development of an adaptive protection algorithm which is based on a physical approach, with the purpose to keep a closed loop aircraft with manual control laws within the actual safe flight envelope, even in the presence of failures or disturbances. Adaptive estimation of the flight envelope guarantees that not only flap changes, but also damage (e.g. icing) and external disturbances such as wind can be taken into account. This method is robust with respect to uncertainties in the estimates for the aerodynamic properties. This updated information makes the flight control laws more self-preserving and prevents loss of control in flight. This development can extend the functional envelope of the nominal law and reduce the need to switch from nominal to alternate law in the presence of certain failures. This algorithm has been applied on a simulation model of a medium range passenger aircraft and the setup has been implemented and evaluated in the DLR Robotic Motion Simulator at the German Aerospace Center as a proof of concept demonstration.

1. Introduction

Safety is a crucial engineering topic in all transportation systems, but especially in civil aviation. Recent aviation accident statistics show that loss of control in flight has become the primary main cause of air accidents, sta (2012). This control loss can have various causes, namely technical malfunctions of hardware components, external meteorological disturbances and/or loss of situational awareness of the flight crew, occurring individually or in combination. Several techniques contribute to avoiding loss of control and achieving an overall fault tolerant aircraft system, Belcastro (2012). On the sensor as well as the actuator side, advanced Fault Detection, Identification and Reconfiguration (FDIR) methods make use of analytical redundancy of measurements to improve performance of on-board monitoring and when needed for reconfiguring systems. This includes also state estimation and aerodynamic model identification. Adaptive control and control allocation techniques can use this information in order to increase the resilience of the system. However, it is also necessary to consider the physical limits of the aircraft flight envelope, which might be affected by the cause(s) of loss of control. In current fly-by-wire civil aircraft, it is common practice to switch from normal law to a degenerate alternate law or even a basic direct law in case of any technical anomaly within the FBW system or severe atmospheric disturbances, Goupil (2011). However, it is especially in these situations that envelope protection becomes crucial. This new technology is not only relevant for civil aircraft, but also for military aircraft and unmanned aircraft. Unmanned aircraft have a larger degree of autonomy, making it even more important that these are able to adapt themselves in the case of failures or upsets, without the need for immediate action by a remote human operator, who might be missing some of the necessary information for making the right steering decisions.

Flight envelope protection is currently a regular part of the flight control laws for modern fly-by-wire aircraft. However, the current types of protections differ between aircraft manufacturers, and they are static. Airbus makes use of hard limitations. This means that it is impossible for a pilot to exceed the envelope boundaries in normal law, see Brière et al. (1995), Favre (1996), Goupil (2011). The conventional flight envelope protection setup for Airbus aircraft in normal law involves high alpha protection, load factor limitation, pitch attitude protection and bank angle protection, A32 (1998). Boeing has a similar setup for flight envelope protections (bank angle protection, stall and overspeed protection), but prefers soft protections, in contrast to Airbus. These deter pilot inputs from exceeding certain predefined limits but do not prohibit them. This means that by using excessive force on the controls, pilots can still violate the flight envelope protection boundaries if they need to, see Bartley (2001). Other flight envelope protection functions

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http://dx.doi.org/10.1016/j.engappai.2017.08.014
Received 15 December 2016; Received in revised form 3 August 2017; Accepted 23 August 2017

have been applied by other civil aircraft manufacturers such as Embraer as well as in military jet aircraft such as the Eurofighter Typhoon, McCuish and Caldwell (1994). Lambregts discusses Envelope Protection (EP) design requirements, as well as functional, safety and performance objectives and design guidelines, see Lambregts (2013).

In the 'Roadmap for Intelligent Systems in Aerospace' AIA (2016), written by the Intelligent Systems Technical Committee (ISTC) of the American Institute of Aeronautics and Astronautics (AIAA), it is mentioned that in the area of real-time monitoring and safety assurance, research is needed in the development and validation of resilient control and mission management systems that enable real-time detection, identification, mitigation, recovery and mission planning under multiple hazards. This resilient control and mission management includes among others dynamic envelope estimation and protection, which could find applications in remotely piloted unmanned aircraft within the next five years. Moreover, an envelope protection system as in Tomlin et al. (1998), Yavrucuk et al. (2009), Balachandran and Atkins (2015) that prevents a pilot or autopilot from stalling or exceeding the safe envelope boundaries can be considered to 'self-preserve' the aircraft with respect to loss of control and provides also a basic form of autonomy. Given the availability of an updated safe flight envelope, it is possible to make these protections adaptive so that they closely match the actual envelope boundaries under various multiple hazards.

A variety of methods for envelope protection have been investigated in previous studies. In Tang et al. (2009), online learning neural networks are used to approximate selected aircraft dynamics which are then inverted to estimate command margins for limit avoidance. The predictive architecture in Krishnakumar et al. (2014) combines an adaptive prediction method to estimate in real-time stability margins and a real-time data-based predictive control margins estimation algorithm. Falkena et al. (2010) focuses on a flight envelope protection system for small aircraft, to allow carefree maneuvering for the less experienced pilot. In Horn et al. (2002), an adaptive limit avoidance system is applied to provide angle of attack and load factor protection. Tekles et al. (2014) presents a dynamic flight envelope protection system based on a command-limiting approach that accounts for aircraft adverse aerodynamics, unusual attitude, and structural integrity. In Tomlin et al. (1998), an application is presented of controller synthesis for hybrid systems to aerodynamic envelope protection and safe switching between flight modes. Each flight mode, which represents a configuration of the dynamic equations describing the motion of the aircraft, is treated as a discrete state with associated continuous, nonlinear dynamics and the safe subset of the state space (which ensures aerodynamic envelope protection) is calculated for each discrete state. Determination of the flight envelope has been done in the literature through various methods and have been discussed extensively in Lombaerts et al. (2015). The most straightforward methods include wind tunnel testing, flight test experiments and high-fidelity model-based computation of attainable equilibrium sets or achievable trim points, Tang et al. (2008), Boskovic et al. (2009), Kwatny and Allen (2012). More complex methods include formulating flight envelope estimation as a reachability problem and solving this with level set methods and Hamilton–Jacobi equations, Lygeros (2004), Mitchell (2008), Kwatny et al. (2009), Tang et al. (2009), Allen et al. (2012), possibly with time scale separation, Kitsios and Lygeros (2005) or semi-Lagrangian level sets, Oort et al. (2011). Alternative methods rely on linearization and region of attraction analysis, Pandita et al. (2009), determining controllability/maneuverability limits in a quaternion-based control architecture, Bacon (2012) or robustness analysis for determination of reliable flight regimes, Shin and Belcastro (2008). An approach suggested by Boeing, as part of the NASA program Dynamic Flight Envelope Assessment and Prediction (DFEAP), uses Control-Centric Modeling, dynamic flexible structure and load models, Urnes et al. (2008). In the frequency domain, stability margins can be estimated in real time via nonparametric system identification, Lichter et al. (2009). More focused techniques inspired by flight dynamics exist as well, such as determining the minimum lateral control speed, Koolstra et al. (2012).

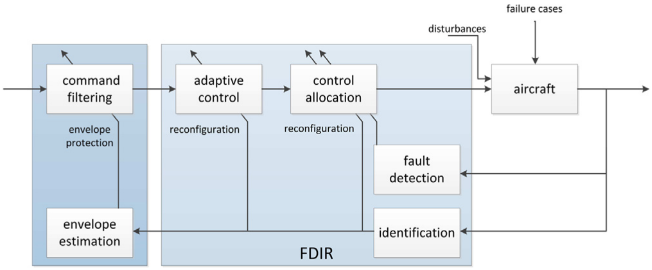

Fig. 1. Global overview of envelope protection in the closed loop architecture including FDIR (Fault detection, Identification and Reconfiguration).

This paper focuses on using a physical approach for the definition of the flight envelope. The adaptive envelope protections are incorporated through separate command filtering in a modular control architecture. This envelope protection setup has been applied on a simulation model of a medium range passenger aircraft and implemented in the robotic motion simulator at the German Aerospace Center DLR as a proof of concept demonstrator. Simulation data are included to support the proof of concept.

The structure of this paper is as follows. A global overview of the closed loop setup is given in Section 2. Section 3 describes a strategy for identifying the aerodynamic parameters which are used for the real time calculation of the envelope boundaries as discussed in Section 4. The implementation of these boundaries as protections in the closed loop architecture as well as in the cockpit displays is presented in Section 5. After a brief introduction of the simulation model in Section 6, some example results for calculating the envelopes are shown in Section 7. Thereafter, Section 8 discusses the implementation in the Robotic Motion Simulator. The concept demonstration and some simulation results are described in Section 9. Finally, conclusions are given in Section 10.

2. Global overview

Fig. 1 illustrates the global overview how envelope protection fits in the closed loop setup together with FDIR (Fault Detection, Identification and Reconfiguration). Fault detection is used to update control allocation based on knowledge about the actuator status. The identification module provides estimates for the aerodynamic derivatives and control efficiencies. The control efficiencies are forwarded to the control allocation block, where adaptive control makes use of the updated aerodynamic derivatives. The identification results are also used by the envelope estimation algorithm. The estimated bounds of the safe flight envelope are then used in the pilot command filtering functions as envelope protection feature. This overview shows how FDIR and envelope protection are complementary to each other.

3. Aerodynamic parameter identification

Since the calculations of the envelope boundaries in Section 4 are model based, a strategy is needed for identifying the necessary aerodynamic parameters. One of the many identification methods that can be used in this context, is the so-called two step method, which has been continuously under development at Delft University of Technology for more than 25 years, see Refs. Chu (2007), Laban (1994), Mulder (1986). There are many other identification algorithms mentioned in the literature like maximum likelihood identification (MLI) and other one step identification routines, but not all of them are applicable on line. One of the few procedures which can be implemented in real time is the so-called filtering method developed at DLR, see Ref. Jategaonkar (2006). This is a joint state and parameter estimation algorithm, but very complex. The advantage of the two step method is that it is easier