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Development and Concept Demonstration of a Physics Based Adaptive Flight Envelope Protection Algorithm ⋆

Thomas Lombaerts * **Gertjan Looye** * **Andreas Seefried** * **Miguel Neves** * **Tobias Bellmann** *

* *German Aerospace Center DLR, Muenchner Strasse 20, 82234 Wessling, Germany (e-mail: {thomas.lombaerts / gertjan.looye / andreas.seefried / miguel.neves / tobias.bellmann} @dlr.de).*

Abstract: This paper 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 is used in the flight control laws to prevent 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 fairly matched A320-type of simulation model and the setup has been implemented in the DLR Robotic Motion Simulator at the German Aerospace Center as a concept demonstrator.

Keywords: Aircraft control; Envelopes; Fault-tolerant systems; Adaptive algorithms; Physical models

1. INTRODUCTION

Safety is a crucial engineering topic in all transportation systems, but especially in aeronautics. 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. 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. 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 lacking 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, bank angle protection and overspeed 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 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 have been applied by other civil aircraft manufacturers such as Embraer as well as in military jet aircraft such as the Eurofighter

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Typhoon, [McCuish and Caldwell (1994)]. Given the availability of an updated safe flight envelope, it is possible to make these limitations adaptive so that they closely match the actual updated envelope boundaries. Lambregts discusses Envelope Protection (EP) design requirements, as well as functional, safety and performance objectives and design guidelines, see [Lambregts (2013)].

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. [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. Determination of the flight envelope has been done in the literature through various methods and have been discussed extensively in [Lombaerts et al. (2015)].

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 fairly matched A320-type of simulation model and implemented in the robotic motion simulator at the German Aerospace Center DLR as a concept demonstrator.

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. ENVELOPE BOUNDARIES

Based on the flight performance and dynamics, it is possible to calculate on-line in flight the envelope protection bounds. This section enumerates the equations as used for calculating these boundaries, a more extensive derivation of these equations can be found in [Lombaerts et al. (2016)]. These equations rely on some aerodynamic derivatives, which need to be identified by a separate algorithm. More information about this identification algorithm can be found in [Schuet et al. (2014)].

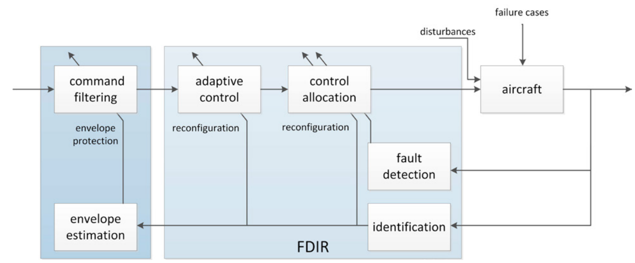

Fig. 1. Global overview of envelope protection in the closed loop architecture including FDIR (Fault Detection, Identification and Reconfiguration)

The minimum calibrated airspeed is calculated as follows:

$$V_{\mathrm{CAS}_{\min}} = \sqrt{\frac{2n_z W}{(C_{L_{\max}} - \Delta_{C_{L_{\max}}})\rho_0 S}} \tag{1}$$

where ρ_0 is the air density at sea level, S is the wing surface area, and $C_{L_{\max}}$ is the maximum lift coefficient with $C_{L_{\max}} = C_{L_0} + C_{L_\alpha}\alpha_{\max}$. $\Delta_{C_{L_{\max}}}$ represents the degree of uncertainty about the maximum lift coefficient for the purpose of robustness. In this calculation the current values for vertical load factor n_z and total aircraft weight W are used, the up-to-date values for the aerodynamic derivatives C_{L_0} and C_{L_α}, as provided by the identification algorithm, as well as the maximum angle of attack $\alpha_{\max}$. Similarly, the protected calibrated airspeed is calculated based on the angle of attack α_{prot}:

$$V_{\mathrm{CAS}_{\mathrm{prot}}} = \sqrt{\frac{2n_z W}{\left(C_{L_{\mathrm{prot}}} - \Delta_{C_{L_{\mathrm{prot}}}}\right)\rho_0 S}} \tag{2}$$

where the protected lift coefficient with $C_{L_{\mathrm{prot}}} = C_{L_0} + C_{L_\alpha}\alpha_{\mathrm{prot}}$.

The maximum load factor depends primarily on the maximum lift coefficient and thus also on the maximum angle of attack:

$$\Delta n_{z_{\max}} = \frac{(C_{L_{\max}} - \Delta_{C_{L_{\max}}})\bar{q}S}{W}\cos\phi - n_Y \sin\phi + \\ -cos\gamma + \frac{T}{W}\sin\alpha\cos\phi \tag{3}$$

where $\bar{q} = 1/2\rho V^2$ is the dynamic pressure, ϕ is the bank angle, n_Y is the lateral load factor, γ is the flight path angle, and T is the aircraft thrust.

For extreme bank angles the following relationship can be derived:

$$\phi_{\max} = \pm\arccos\left(\frac{m\,(g\cos\gamma + V\dot{\gamma})}{T\sin\alpha + (C_{L_{\max}} - \Delta_{C_{L_{\max}}})\bar{q}S}\right) \tag{4}$$

where m is the total aircraft mass and g is the gravity constant. In these calculations the current values for airspeed V and its derivative $\dot{V}$, Thrust T, angle of attack α and flight path angle γ are used. For normal maneuvers of a conventional civil airliner, the maximum bank angle is not expected to exceed 35°.

Reducing speed will restrict the available bank range to lower values of $\pm\phi_{\max}$. At stall speed, no bank authority will be left.

The minimum and maximum flight path angles are defined as: