Modeling, Analysis, and Control for Upset Recovery - from System Theory to Unmanned Aircraft Flight

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Abstract

Upset flight dynamics are characterised by unstable, highly nonlinear behaviour of the aircraft aerodynamic system. As upsets often lead to in-flight loss-of-control (LOC-I) accidents, it still poses a severe threat to today's commercial aviation. Contributing to almost every second fatality in civil aviation while representing merely 10% of the total accidents (both fatal and nonfatal), the International Air Transport Association has classified LOC-I as the "highest risk to aviation safety". Considerable effort has been undertaken in response by academics, manufacturers, commercial airlines, and authorities to predict and prevent LOC-I events as well as recover from upset conditions into the nominal flight envelope. As result, researchers from both aeronautical engineering and system theory have made significant contributions towards aviation safety; however, approaches from engineering and theory are rather disparate. This thesis therefore focuses on the application and transfer of system theoretical results to engineering applications.

In particular, we have found simple polynomial models for aircraft dynamics, despite common in the system theoretical literature, failing to represent full-envelope aerodynamics accurately. Advanced fitting methods such as multi-variate splines, on the other hand, are unsuitable for some of the proposed functional analysis methods. Instead, a simple piecewise defined polynomial model proves to be accurate in fitting the aerodynamic coefficients for low and high angles of attack. State-of-the-art bifurcation analysis and analysis based on sum-of-squares programming techniques are extended for this class of models and applied to a piecewise equations of motion of the Generic Transport Model (GTM). In the same spirit, we develop a model for a small, fixed-wing aircraft based on static continuous fluid dynamics (CFD) simulations. In the lack of dynamic coefficients from CFD, we identify a pitch-damping model comparing bifurcation analysis and flight data that predicts well dynamics and stability of deep-stall flight.

Previous developments in sum-of-squares programming have been promising for the certification
of nonlinear dynamics and flight control laws, yet their application in aeronautical engineering halted. In combination with piecewise polynomial modeling, we are able to re-apply this technique for analysis in an accurate but computationally feasible manner to verify stable recovery. Subsequently, we synthesise inherently stable linear and polynomial feedback laws for deep-stall recovery. We further extend the estimation of regions of attraction for the piecewise polynomial model towards an improved algorithm for local stability analysis of arbitrary switching
systems, such as splines, thus making our work available for future analysis and certification of highly accurate algebraic models.

With highly nonlinear dynamics and critical state and input constraints challenging upset recovery, model-predictive control (MPC) with receding horizon is a powerful approach. MPC further provides a mature stability theory contributing towards the needs for flight control certification.

Yet, for realistic control systems careful algebraic or semi-algebraic considerations are necessary in order to rigorously prove closed-loop stability. Employing sum-of-squares programming,
we provide a stability proof for a deep-stall recovery strategy minimising the loss of altitude during recovery. We further demonstrate MPC schemes for recovery from spiral and oscillatory spin upsets in an uncertain environment making use of the well-known and freely available high-fidelity GTM desktop simulation.

The results of this thesis are thus promising for future system theoretic approaches in modeling, analysis, and control of aircraft upset dynamics for the development and certification of flight control systems in order to prevent in-flight loss-of-control accidents.

Keywords

Nonlinear control; upset recovery; aerodynamics modeling; stability analysis; unmanned aircraft; system theory.