Incremental Nonlinear Adaptive Flight Control with Online System Identification

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Background

Research into previous flight accidents and investigations of the fault-tolerant flight control (FTFC) strategies used suggest that an aircraft, under many post-failure circumstances, can still achieve a certain level of flight performance using the remaining valid control effectors. However, the control authority or the safe flight envelope of the aircraft will inevitably shrink due to structural/actuator failures. Therefore, to avoid the flight accidents caused by Loss-of-control in flight (LOC-I) , it is necessary to employ suitable non-conventional control strategies to extract the most flight potential from a post-failure aircraft . One such promising control strategy is the fault-tolerant flight control (FTFC).

Main Research Questions

1. How can the candidate function approximation methods, i.e. multivariate simplex B-splines (MVSB) and kernel methods, be improved in terms of approximation accuracy and computational efficiency, to meet the need of model-based adaptive control and online flight envelope protection (OFEP)?
2. What are the benefits of using an acceleration measurements-based control approach, i.e. the sensor based backstepping, as an alternative to a model-based adaptive control approach, when designing a reconfigurable flight controller to deal with aircraft failures in a generic fault-tolerant flight control system?

Definition of a model-based FTFC system

A model-based FTFC system, see Fig.1, is an advanced model-based flight control system which can obtain failure knowledge using a fault detection & isolation unit, and improve the situation awareness of a pilot or an internal controller by indicating the current safe flight envelope. It can accomplish the demanded flight tasks after accommodating ongoing fault scenarios using a non-conventional reconfigurable flight control law.

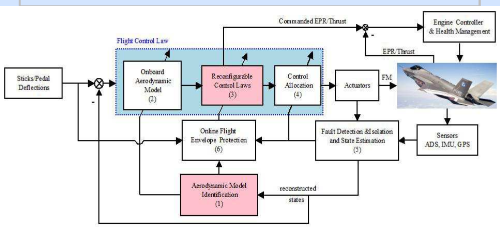

Fig.1.A modern model-based fault-tolerant flight control system, the blocks with the pink shading are the main focuses.

Objectives and outlines

1. An online global valid aerodynamic model is required for a full-envelope model-based adaptive flight control system and an online flight envelope protection unit.
2. Reconfiguration mechanisms include not only adaptive compensation using updated model information but also an adaptive incremental control strategy.

Advantages of multivariate simplex B-splines

1. Unlike ordinary tensor product splines, simplex B-spline based method can deal with scattered data sets without needing pre-treatment, see Fig.2.
2. Simplex B-spline based method has proven to have a high approximation power. Its approximation power can be increased by increasing the density of the simplices in a triangulation and the polynomial order.
3. This method can guarantee a smooth transition between different local per-simplex models. Directional derivative can be easily calculated.
4. Fourthly, this method allows interpolation between simplices or extrapolation outside of the well-studied subdomains with a boundary predetermined by the a priori knowledge.

Part I: Multivariate Simplex B-splines

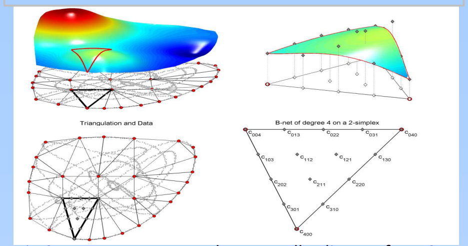

Fig.2. B-net structure and an overall spline surface, 2-D

Achievements on MVSB

1.To enhance the computational efficiency of the parametric model identification methods using multivariate simplex B-spline polynomials, two recursive linear regression schemes were developed: a substitution based solver based on the kernel space of the smoothness constraint matrix and a recursive sequential approach based on the updating of a per-simplex local model at each sampling time. These two new methods were validated using simulated flight test data generated using a high-fidelity nonlinear model of an F-16 aircraft. Both new methods can be 10 times faster than the equality constraint recursive least squares (ECRLS) MVSB method.

2. A tensor-product simplex (TPS) B-spline model structure is extended from a single dimension case into a general multi-dimensional case. TPS B-splines have proven to be able to yield higher approximation accuracy with less B-coefficients compared to the standard MVSB method.

Part II: Recursive parametric kernel methods

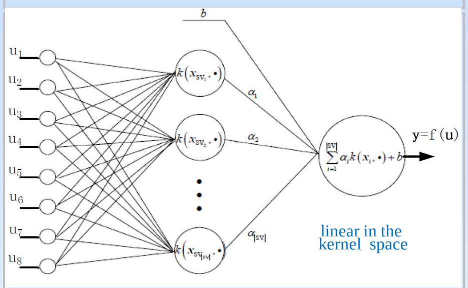

Fig.3. A generic structure of a kernel model such as a support vector regression or RBF neural networks, 8-D

Achievements on recursive kernel methods

An open issue for recursive kernel methods is how the optimum or optimal set of kernels can be determined in a computationally efficient way. An improved recursive reduced least squares support vector regression method is used to provide kernel centers for a classical recursive kernel method. In addition, to better capture the local data trends, the benefits of expanding the local kernels are investigated. Two new methods namely WV-LSSVR and GPK-LSSVR were developed and then validated using public available benchmark data. The results show that both of them can lead to higher approximation accuracy than a k-means clustering based recursive kernel method.

Part III: Acceleration measurement-based incremental nonlinear control (AMINC)

The AMINC methods include a regular incremental backstepping (or incremental nonlinear dynamic inversion, INDI) and the sensor based backstepping (SBB). The SBB control approach is the preferred incremental approach during my work reported in this thesis. Thanks to the approximate adaption property/nature of the incremental control strategy, the SBB approach is supposed to be able to accommodate large model uncertainties caused by sudden structural or actuator damage occurring in an aircraft.

1. Merits of an SBB approach

This singular perturbation theory based incremental approach requires angular acceleration measurements, but it does not require accurate online aerodynamic model information. The reliability of an aerodynamic model cannot always be guaranteed during a transition period when major structural or actuator failures happen to an aircraft or when high maneuverable flight tasks are performed.

2.Two-loop attitude controller designed using an SBB approach

The SBB control approach was applied to design a 2-loop attitude controller for the RECOVER Boeing 747 model with a focus on accommodating structural or actuator failures. The aircraft system can be viewed as a cascaded system. Correspondingly, the controller has the structure as shown in Fig.4.

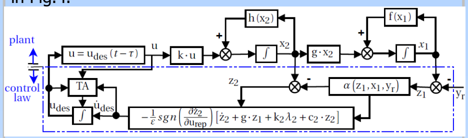

Fig.4. Control diagram for a joint SBB attitude controller

3. Relation between incremental backstepping and SBB

Using the regular incremental backstepping (IBKS) and the SBB approach, the final control laws take the following forms:

$$\Delta \mathbf{u} = -\mathbf{B}_2^{-1}\cdot(\mathbf{c}_2\mathbf{z}_2 + [\dot{\mathbf{x}}_2 - \dot{\mathbf{x}}_{2r}] + \mathbf{B}_1\mathbf{z}_1)$$

$$\dot{\mathbf{u}} = -\frac{1}{\varepsilon} sign\left(\frac{\partial \dot{z}_2}{\partial u}\right)(\mathbf{c}_2\mathbf{z}_2 + [\dot{\mathbf{x}}_2 - \dot{\mathbf{x}}_{2r}] + \mathbf{B}_1\mathbf{z}_1)$$

The following relation between them was found:

$$\Delta \mathbf{u} \cong \dot{\mathbf{u}}\cdot \Delta T$$

However, the SBB approach has a time scale parameter, which could simplify the tuning process when choosing controller gains.

4. Validation setups and a 4-loop autopilot

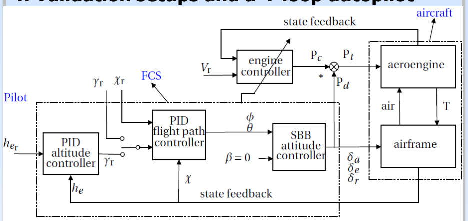

Fig.5. Control structure of a four-loop autopilot for the RECOVER model with a double-loop joint SBB attitude controller at the center.

Two benchmark fault scenarios selected:

a). EL AL flight 1862 engine separation scenario

b). Rudder runaway fault scenario

Achievements on the SBB attitude controller

The two-loop SBB angular control approach has been validated using the RECOVER model with a focus on demonstrating its fault tolerant capability using the benchmark fault scenarios. The SBB angular controller has proven to be able to guarantee a zero tracking error performance when the aircraft encounters the engine separation fault. When the aircraft is suffering from the rudder runaway fault, the SBB double-loop attitude controller can still stabilize the closed-loop aircraft system. However, the sideslip angle stays at a non-zero value due to the undesired yawing moment introduced by the stuck rudder. The SBB approach provides an alternative to an adaptive NDI method or an sliding mode reconfigurable control approach for the purpose of fault tolerant control.

Progress and Objectives

Dissertation writing has been finished.

Publications

1. L.G.Sun, C.C. de Visser, Q.P.Chu, J.A.Mulder, Online Aerodynamic Model Identification using a Recursive Sequential Method for Multivariate Splines, Journal of Guidance,Control, and Dynamics, Vol.36, No. 5, pp.1278-1288, 2013 (doi:10.2514/1.60375)
2. L.G.Sun, C.C. de Visser, Q.P.Chu, W.Falkena, Hybrid Sensor Based Backstepping Control Approach with its Application to Fault-Tolerant Flight Control,Journal of Guidance,Control, and Dynamics,Vol.37, No. 1, pp.59-71, 2014 (doi:10.2514/1.61890)
3. L.G.Sun, C.C. de Visser, Q.P.Chu, J.A.Mulder, A novel adaptive kernel method with kernel centers determined by a support vector regression approach, Neurocomputing, Vol. 124, pp.111-119, 2014(doi:http://dx.doi.org/10.1016/j.neucom.2013.07.023)
4. L.G.Sun, C.C. de Visser, Q.P.Chu, J.A.Mulder, A Joint Sensor Based Backstepping Approach For Fault-Tolerant Flight Control of a Large Civil Aircraft,Journal of Guidance,Control, and Dynamics, Under Review, 2013

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