Incremental Nonlinear Adaptive Flight Control with Online System Identification

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 controller. 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 control system?
2. What are the benefits of using an acceleration measurement-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 situational 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 black blocks with the inner 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

Achievements on MVSB

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 WLS-LSVR and GPR-LSVR 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 II: Recursive parametric kernel methods

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 strategy 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.


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Part II: Recursive parametric kernel methods

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


Two-loop SO approach 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.

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:

\[
\Delta u = -B_1 \Delta e + (B_1 - B_2) \sum_{i=1}^{k-1} k_{i-1} \Delta e_i + B_2 \Delta e_k
\]

The following relation between was found: \( \Delta u = B \cdot \Delta T \)

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

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.