National Aeronautics and Space Administration

Integrated Resilient Aircraft Control

Pilot Evaluation of Adaptive Control in Motion-Based Flight Simulator

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Objectives

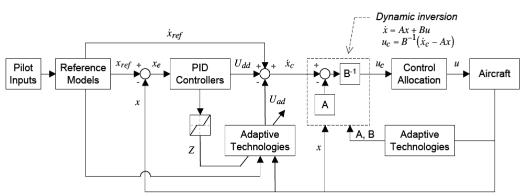
The objective of this work is to assess the strengths, weaknesses, and robustness characteristics of several MRAC (Model-Reference Adaptive Control) based adaptive control technologies garnering interest from the community as a whole. To facilitate this, a control study using piloted and unpiloted simulations to evaluate sensitivities and handling qualities was conducted. The adaptive control technologies under consideration were **ALR** (Adaptive Loop Recovery), **BLS** (Bounded Linear Stability), **Hybrid** Adaptive Control, **L_1**, **OCM** (Optimal Control Modification), **PMRAC** (Predictor-based MRAC), and traditional **MRAC**.

Technical Challenges

The primary technical challenges were to tune and integrate the separate adaptive control technologies for a handling qualities evaluation. For this purpose it was necessary to mature each technology to handle a full-flight envelope. Tuning of the various controllers then required developing a simple but intuitive tuning methodology based on design requirements and simulation studies.

Technical Approach

- Integrate each adaptive control technology into a common baseline control architecture (robust dynamic inversion controller).



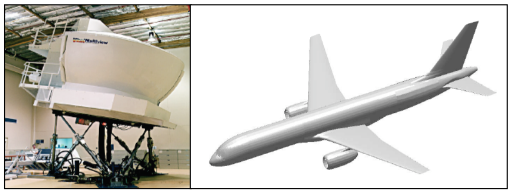
General Dynamic Inversion Control Architecture

- Define each adaptive control technology for a common set of basis functions (used for parameterizing the model uncertainty).
- Tune each adaptive technology to achieve a 50 ms time-delay margin.
- Require that the design parameters for each controller remain constant.
- Tune using evaluations of simulated aircraft performing a lateral, longitudinal, directional doublet maneuver at 10,000 ft./140 Kts. and 10,000 ft./250 Kts.

- Evaluation Metric: error between system response ($x(t)$) and reference model ($x_m(t)$).

$$M_5 = \frac{\|x(t) - x_m(t)\|_{L_2}}{\|x_m(t)\|_{L_2}} = \frac{\sqrt{\sum (x(t) - x_m(t))^2 \Delta t}}{\sqrt{\sum (x_m(t))^2 \Delta t}}$$

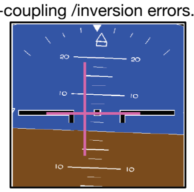
- Grossly tune each adaptive control technology by hand to achieve best possible performance for above metric while maintaining required time-delay margin.
- Design a simulation study using NASA test pilots to evaluate the characteristics of each adaptive technology.
- Use a full-motion flight simulator, the *Generic Transport Model* (GTM), and failure scenarios in the design of the simulation study.



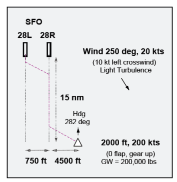
ACFS full motion simulator and GTM aircraft 3D model

Experiment for Cooper-Harper (CH) Handling Qualities Evaluations

- Two tasks: Flight director capture task for large amplitude maneuvers and an approach and landing task with a side-step maneuver.
- Adequate/Satisfactory rating for capture task based on number of captures. Rating for landing based on sink rate, crab angle, bank angle, centerline offset, and touchdown distance (all measured at touchdown).
- Capture task for two flight conditions: 1) 10,000 ft., 140 Kts. and fully configured for landing (full flaps and gear); and 2) 10,000 ft. and 250 Kts.
- Failures include lose of 50% of left horizontal tail, artificial aileron/elevator cross-coupling, baseline controller inversion errors, and combination cross-coupling /inversion errors.



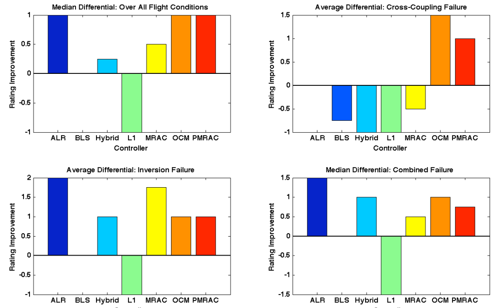
PFD for Capture Task



Approach and Landing Task

Results

- ALR, OCM, and PMRAC provided improved ratings over the baseline controller in all instances.
- L_1 implementation exhibited marginal directional stability at high airspeeds for the inversion and combined failures and was generally unstable at lower airspeeds. This is reflected in the CH ratings as further tuning and investigation is required.
- Hybrid, BLS, and MRAC gave mixed ratings of improved, degraded, and unaffected performance.
- Hybrid, BLS, and MRAC performed better with the inversion failure and the combined failure then with the cross-coupling failure alone.



CH Rating Differential for Various Failures (positive number denotes a CH improvement/reduction)

Adaptive Technology	Pilot Comments/Observations (Strengths)	Pilot Comments/Observations (Weaknesses)
Adaptive Loop Recovery	Described as predictable, responsive, and stable.	Some sluggishness observed, with better characteristic exhibited in pitch (than in roll).
Bounded Linear Stability (BLS)	Described as being easier to control compared to baseline.	Described as having a sluggish behavior (requiring leading) with some cross-coupling. Observed to be prone to PIOs (particularly at slower airspeeds).
Hybrid Adaptive Control	Described as having less overshoot. Performs well in moderate and severe turbulence.	Described as having a wobble, pulse, ratcheting behavior, or small motion artifacts.
L_1 Adaptive Control	Easy to tune (because of preserved time-delay margins). Good performance for small B-Matrix gain variations.	Directional instabilities observed (particularly at slower airspeeds). Described as having slow response (or time-delays) and cross-coupling.
Model Reference Adaptive Control (MRAC)	Improved handling qualities observed (particularly at higher airspeeds).	Described as having a sluggish response as well as some overshoot, leading to PIO tendencies.
Optimal Control Modification (OCM)	Described as more responsive and predictable in some instances.	Some residual motion and overshoot observed, requiring some shaping of the control inputs.
Predictor Based Model Reference Adaptive Control	Described as having very good response in some instances (particularly under nominal conditions).	Described as having a bobble / wobble (in pitch and roll). Found to be very time-delay sensitive (resulting in small adaptation gains).

Pilot General Comments