Adaptive Flight Control for Aircraft Safety Enhancements
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Approximate Stability Margin Analysis of Hybrid Direct-Indirect Adaptive Control

**Motivation**
Despite 5 decades of research, adaptive control still cannot gain acceptance in safety-critical control systems. Challenges include:
- Complex nonlinear behaviors vs. well-understood linear systems
- Lyapunov theory cannot predict boundedness in presence of unmodeled dynamics
- Metrics for stability and performance not yet available
- No guidance on adaptive gain selection for trade-off between performance and robustness

**Technical Approach**
- Hybrid (composite) direct-indirect adaptive control provides a flexible framework
  - Indirect adaptation via recursive least-squares (RLS) parameter estimation
  - Direct adaptation with lower adaptive gain to improve robustness

**Solution**
Adaptive control laws for handling actuator failures:
- State tracking:
  - State feedback - low complexity, most assumptions
  - Signal boundedness and asymptotic tracking
- Output tracking:
  - Output feedback - highest complexity, fewest assumptions

**Example Application – GTM (Joshi, Khong)**
- One of two elevators locks in unknown position at t = 2 sec
- Square wave elevator command applied at t = 10 sec
- Remaining operational elevator seamlessly takes over for failed elevator

**Current Work in Progress**
- Use system identification techniques to build a pilot model that changes as system dynamics change
- Pilot in the loop with an adaptive controller while explicitly incorporating the pilot.
- For system stability and performance analysis, model the pilot as an adaptive controller

**Conclusions**
- Direct MRAC can compensate for unknown actuator failures:
  - Signal boundedness and asymptotic tracking
  - State or output tracking using state feedback has manageable level of complexity
- Analytical evaluation and performance of a closed-loop system with an adaptive controller while explicitly incorporating the pilot.

**Implications**
- Analytically evaluate stability and performance of a closed-loop system with an adaptive controller while explicitly incorporating the pilot.
- Provide a framework for analytical analysis of interaction of two adaptive elements in a closed-loop system with changing dynamics
- Identify and characterize interactions leading to potentially conflicting actions (e.g., flight and structural control systems or flight and propulsion control systems)
- Contribute to functional allocation between pilot and adaptive control schemes as well as pilot's situational awareness of system's capabilities

**Direct Adaptive Control With Unknown Actuator Failures**

**Objective**
New direct adaptive control methods are being developed for systems with unknown actuator failures:
- Theoretically guaranteed stability and tracking performance

**Technical Challenges**
- Mathematical modeling, formulation, and analytical framework development
- Accommodation of actuator failures, disturbances, model uncertainties, actuator saturation

**Technical Approach**
Direct model reference adaptive control (MRAC):
- Formulations with increasing complexity and decreasing assumptions
  - Actuator failures of unknown magnitude and time of occurrence
  - State tracking with state feedback
  - Output tracking with state feedback
  - Output tracking with output feedback

**Actuator Failure Models**
- Loss of effectiveness: \( \eta(t) \in [0.01, 0.1] \) for \( t = 10 \text{sec} \) pattern (which actuators have failed) are unknown

**Solution**
Adaptive control laws for handling actuator failures:
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**Conclusions**
- Direct MRAC can compensate for unknown actuator failures:
  - Signal boundedness and asymptotic tracking
  - State or output tracking using state feedback has manageable level of complexity
- Continuing research:
  - Accommodation of multiple failures; disturbances; actuator saturation; unmodeled dynamics; damage; nonlinear systems, adaptive propulsion control; application to full GTM math model

**Adaptive Control with Adaptive Pilot Element: Stability and Performance Implications**

**Motivation**
Different adaptive control approaches on different platforms exhibited unpredicted interactions with pilot-in-the-loop (PIL) systems.
Adaptive controller will have full control authority.

**Technical Approach (Trujillo, Morelli, Gregory)**
Mathematically define the pilot as an adaptive controller.

For system stability and performance analysis, model the pilot as an adaptive controller; therefore, analyze a system consisting of two adaptive controllers of potentially different architectures. In addition, this analysis will provide:
- Design requirements on adaptive controller to compliment pilot's actions
- Predicted analytical bounds on pilot-in-the-loop task specific performance
- Framework for analyzing interaction between two adaptive elements will facilitate exploration of problematic adaptive controller/pilot model interactions to explore these problematic interactions in detail in simulation and/or flight test (akin to worst case uncertainty in linear robustness analysis guiding detailed Monte Carlo strategies).

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**Conclusion**
- Hybrid adaptive control can enhance adaptation by reducing both modeling and tracking errors at the same time
- Bounded linear stability analysis can provide practical conservative estimates of stability margin

**Simulation**
- Phase Margin
- Time-Delay Margin
- Metrics-Driven Adaptation

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