Adaptive Flight Control for Aircraft Safety Enhancements

Nhan Nguyen, Irene Gregory, Suresh Joshi

Integrated Resilient Aircraft Control

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

Certification of adaptive control is a major V&V hurdle to overcome

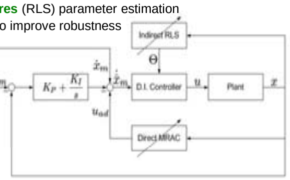
Technical Approach

- **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

Plant: $\dot{x} = A_p x + B_p u + f(x)$

Estimator Model:

$\dot{\hat{x}} = Ax + Bu + \Theta^\top \Phi + u_{ad}$



RLS Parameter Estimation

$$\dot{\Theta} = -\frac{1}{1+\Phi^\top R\Phi} R\Phi\left(\Phi^\top\Theta - \varepsilon^\top\right)$$

$$\dot{R} = -\frac{1}{1+\Phi^\top R\Phi} R\Phi\Phi^\top R$$

Direct Adaptive Control

$$u_{ad} = W^\top \beta(x)$$
$$\dot{W} = -\Gamma\beta e^\top P b$$

- **Bounded linear stability method** provides piecewise approximate LTI margin analysis in a **moving time window** via the use of **Comparison Lemma**

$$\frac{d}{dt}\begin{bmatrix} e \\ z_1 \\ z_2 \end{bmatrix} \le \begin{bmatrix} A_c & b & b \\ -\Gamma\beta_0^2 b^\top P & 0 & 0 \\ 0 & 0 & -a \end{bmatrix}\begin{bmatrix} e \\ z_1 \\ z_2 \end{bmatrix} + \begin{bmatrix} b\Delta_2 \\ \varepsilon_1 \\ \varepsilon_2 \end{bmatrix}$$

$$\beta_0^2 = \frac{1}{T}\int_{t_0-T}^{t_0} \beta^\top\beta\, dt \qquad \Phi_0^2 = \frac{1}{T}\int_{t_0-T}^{t_0} \Phi^\top\Phi\, dt$$

Persistent Excitation

$$R_0 = \lambda_{min}(R) \qquad a = \frac{R_0\Phi_0^2}{1+R_0\Phi_0^2} > 0$$

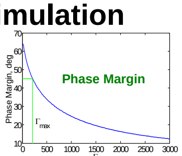
Approximate Local Transfer Function

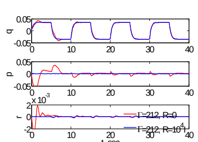
$$G(s) = \left(sI - A_p + B_p\hat{B}_p^{*-1}\hat{A}_p^*\right)^{-1} B_p\hat{B}_p^{*-1}\left(K_p + \frac{K_i + \Gamma\beta_0^2 P_{22}}{s} + \frac{\Gamma\beta_0^2 P_{12}}{s^2}\right)$$

$$G^*(s) \approx \frac{K_p s^2 + \left(K_i + \Gamma\beta_0^2 P_{22}\right)s + \Gamma\beta_0^2 P_{12}}{s^3} \quad \text{if} \quad \hat{A}_p^* \to A_p,\ \hat{B}_p^* \to B_p$$

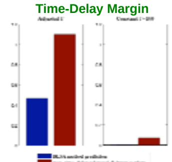
- Use approximate transfer function to estimate local stability margin for a moving time window

Simulation





Time-Delay Margin



Metrics-Driven Adaptation

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

Nguyen et al., Flight Dynamics and Hybrid Adaptive Control of Damaged Aircraft, Journal of Guidance, Control, and Dynamics
Nguyen & Boskovic, Bounded Linear Stability Margin Analysis of Nonlinear Hybrid Adaptive Control, American Control Conference 2008

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: $u_j(t) = k_j(t)v_j(t),\ k_j(t) \in [0,1],\ t \ge t_j$
- Control surface locked in unknown position: $u_j(t) = \bar{u}_j,\ t \ge t_j, \quad j = 1,2,\ldots,m$
- Failure values k_j, $\bar{u}_j$, and failure time t_j, pattern (which actuators have failed) are unknown

Solution

Adaptive control laws for handling actuator failures:

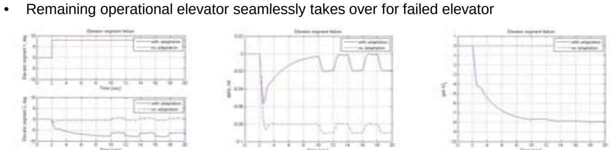
- State tracking: $\lim_{t\to\infty}\{x(t) - x_m(t)\} = 0$
  - State feedback - low complexity, most assumptions

$$v(t) = K_1^T x(t) + k_2 r(t) + k_3(t);$$
$$\dot{k}_{1j} = -\text{sgn}(k_{s2j}^*)\Gamma_{1j} x(t) e^T(t) P b_M; \quad e = x - x_m$$
$$\dot{k}_{2j} = -\text{sgn}(k_{s2j}^*)\gamma_{2j} r(t) e^T(t) P b_M;$$
$$\dot{k}_{3j} = -\text{sgn}(k_{s2j}^*)\gamma_{3j} e^T(t) P b_M;$$
$$P = P^T > 0;\ PA_m + A_m^T P = -Q < 0;$$
$$\Gamma_{1j} = \Gamma_{1j}^T > 0;\ \gamma_{2j}, \gamma_{3j} > 0;\ j = 1,2,\ldots m$$

- Output tracking: $\lim_{t\to\infty}\{y(t) - y_m(t)\} = 0$
  - State feedback - higher complexity, fewer assumptions
  - 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



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

NRA Partner: Gang Tao, University of Virginia

Adaptive Control with Adaptive Pilot Element: Stability and Performance Implications

Motivation

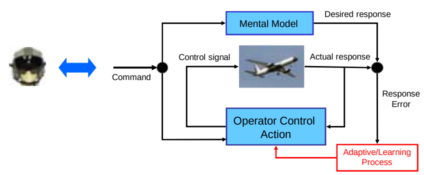
Different adaptive control approaches on different platforms exhibited unpredicted interactions with pilot-in-the-loop (IFCS F-15, Navy F/A-18C)

Adaptive controller will have full control authority

These combined factors have significant implications for closed loop system stability and performance as well as present potentially significant V&V challenge.

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 identification of problematic adaptive controller/adaptive pilot model interactions → explore these problematic interactions in detail in a simulation and/or flight test (akin to worst case uncertainty in linear robustness analysis guiding detailed Monte Carlo)

Current Work in Progress

- Use system identification techniques to build a pilot model that changes as system dynamics change → initial model of a pilot as an adaptive element
- Pilot in the loop with an Λ_1 adaptive controller on the GTM in the simulation and flight test. *(scheduled for Dec. 2008)*
  - Analytically calculate stability robustness margins of an Λ_1 adaptive controller and compare to those obtained from flight data
- Adaptive pilot model from system identification will fly the maneuvers from GTM flight test in batch simulation
  - Compare adaptive pilot model performance to research pilot performance from flight data

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 mode 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

NASA Aviation Safety Technical Conference, Denver, CO, Oct 21 - 23, 2008