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Flight Research into Simple Adaptive Control on the NASA FAST Aircraft

Abstract / References

A series of simple adaptive controllers with varying levels of complexity were designed, implemented and flight tested on the NASA Full-Scale Advanced Systems Testbed (FAST) aircraft. The controllers were evaluated against several simulated failures scenarios. Preliminary lessons learned from the development and flight testing are presented.

[1] Ioannou, P.A. and Sun, J., *Robust Adaptive Control*, Prentice Hall 1996.

[2] McRuer, D., Ashkenas, I., & Graham, D., *Aircraft Dynamics and Automatic Control*, Princeton University Press 1973.

[3] Miller, C. "Non-Linear Dynamic Inversion Baseline Control Law for FAST Control Research: Architecture and Performance Predictions", AIAA 2011.

[4] Nguyen, N., "Asymptotic Linearity of Optimal Control Modification Adaptive Law with Analytical Stability Margins", AIAA 2010.

[5] Fields, D. et. al. "Limited Handling Qualities Evaluation of Inter-axis Control Coupling", AFFTC-TIM-10-03, 2010.

Experiment Background

2009, Apr: NASA's Integrated Resilient Aircraft Control (IRAC) project disseminated a request for information (RFI) on potential flight experiments to the adaptive controls community

2009, Aug: The IRAC project hosted a workshop to discuss the RFI and responses from Industry, Academia and Government

2009, Sep: A decision letter was released outlining the IRAC project's research focus for flight experiments on the Full-Scale Advanced Systems Testbed (FAST):

1. **simple yet effective adaptive algorithms** that may represent a starting point for the verification and validation of adaptive flight controls
2. **pilot awareness and interaction** with the adaptive algorithm
3. **interaction between the controller and structural loads** (both static and dynamic)

2011, Dec – Jan: Completed ten research flights, primarily focused on simple adaptive control, with some aspects of pilot interaction

Experiment Methodology

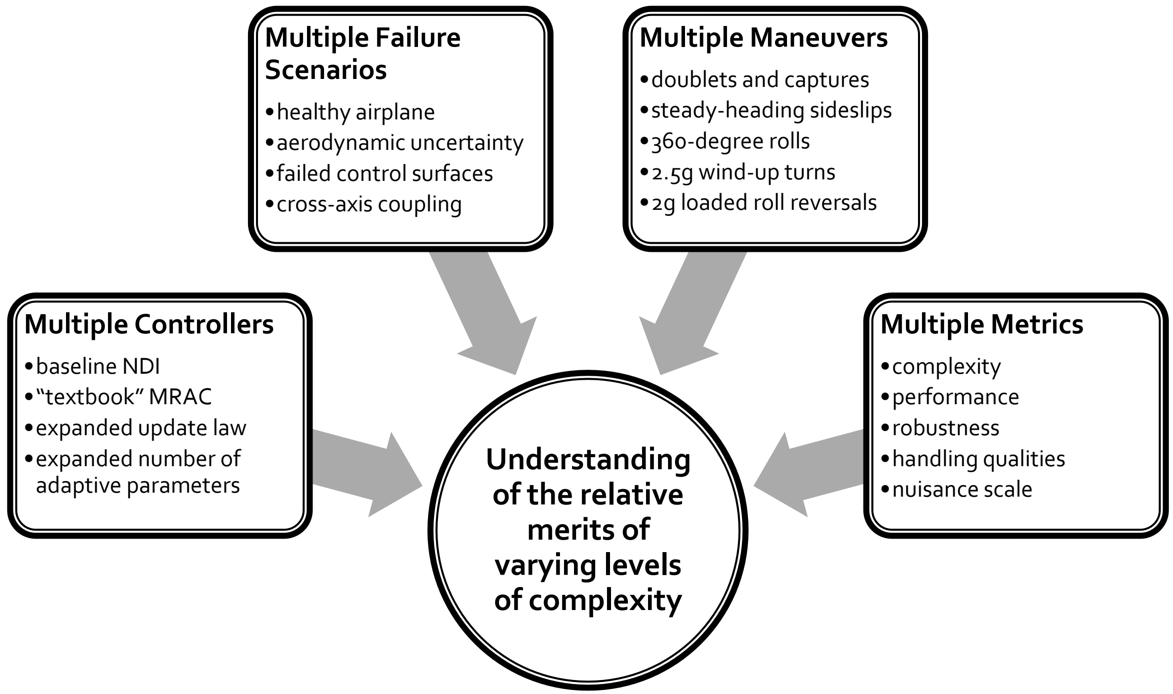
Explore Adaptive Controller Complexity through Flight Research

<u>ASSUMPTION</u>
Simplification → lower implementation and verification costs, improved safety and greater likelihood of acceptance by the industry

The necessary and appropriate level of complexity is unique to each control application.

The goal of this experiment is to add to the relatively small set of flight data for adaptive controls on piloted aircraft, for use by future designers.

It is not a demonstration of the effectiveness of adaptive control nor a showcase of the someone's latest / greatest algorithm.



NDI with MRAC Augmentation

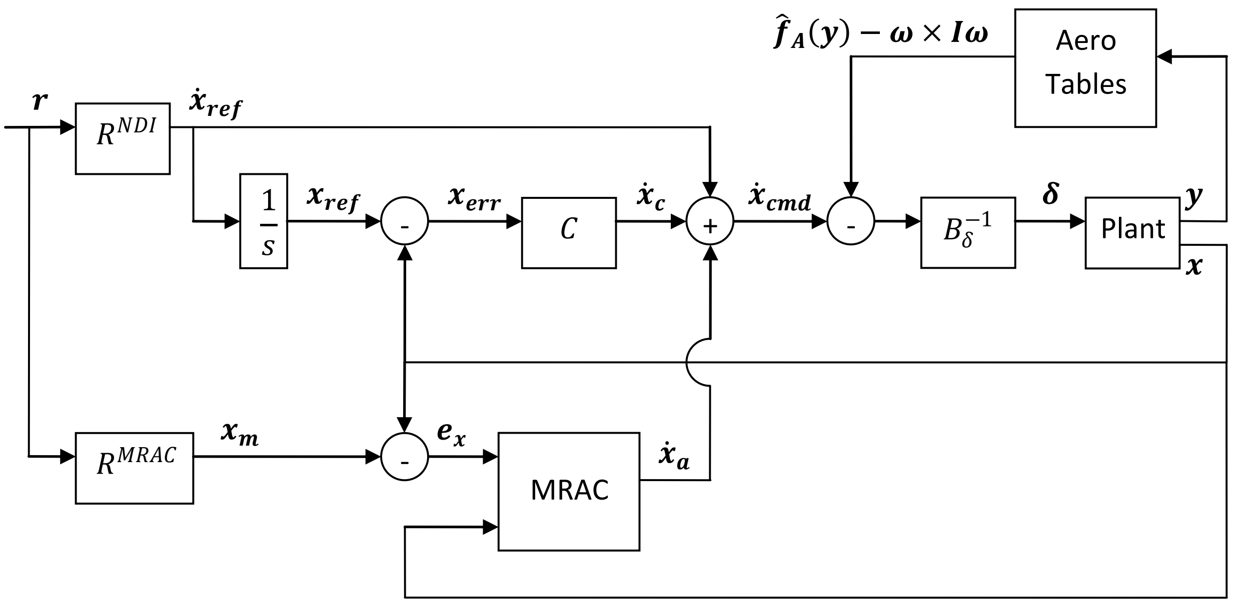
Roll Axis

$$R_p: \frac{\dot{p}_{ref}}{r_p} \cong \frac{\dot{p}_m}{r_p} = \frac{s}{s+\omega_p}$$

$$r_p(t) = \left(\frac{r_{max}}{\alpha}\right) k_p \omega_p \delta_{ap}(t)$$

$$\dot{p}_c(t) = \omega_p \left(p_{ref}(t) - p(t)\right)$$

$$\dot{p}_a(t) = \hat{\theta}_p(t) p(t) + \hat{\sigma}_p(t)$$



Pitch Axis

$$R_q: \frac{\dot{q}_{ref}}{r_q} \cong \frac{\dot{q}_m}{r_q} = \frac{s^2}{s^2 + 2\zeta_q \omega_q s + \omega_q^2}$$

$$r_q(t) = k_q \omega_q^2 \left(\delta_{ep}(t) + L_\alpha \int \delta_{ep}(t) dt\right)$$

$$\dot{q}_c(t) = 2\zeta_q \omega_q \left(q_{ref}(t) - q(t)\right) + \omega_q^2 \int \left(q_{ref}(t) - q(t)\right) dt$$

$$\dot{q}_a(t) = \hat{\theta}_{q1}(t) \int q(t) dt + \hat{\theta}_{q2}(t) q(t) + \hat{\sigma}_q(t)$$

Rotational Acceleration Command Vector

$$\dot{x}_{cmd}(t) = \dot{x}_{ref}(t) + \dot{x}_c(t) + \dot{x}_a(t) = \begin{bmatrix} \dot{p}_{ref}(t) + \dot{p}_c(t) + \dot{p}_a(t) \\ \dot{q}_{ref}(t) + \dot{q}_c(t) + \dot{q}_a(t) \\ \dot{r}_{ref}(t) + \dot{r}_c(t) \end{bmatrix}$$

Dynamic Inversion

$$\delta(t) = B_\delta^{-1}\left(I\dot{x}_{cmd}(t) + \omega(t) \times I\omega(t) - \hat{f}_A\big(y(t)\big)\right) + \delta_0$$

MRAC Design

Roll Axis

Tracking Error

$$e_p(t) = p_m(t) - p(t)$$

sMRAC Update Law (**s**imple MRAC)

$$\dot{\hat{\theta}}_p = \Gamma_\mathrm{p} e_p P_p B_{m_p} p$$

onMRAC Update Law
(optimal control modification / normalization)

$$\dot{\hat{\theta}}_p = \frac{\Gamma_\mathrm{p}}{1 + R_{\theta_p} p^2}\left(e_p P_q B_{m_q} p + \nu_{\theta_q} p^2 \hat{\theta}_p B_{m_p}^T P_p A_{m_p}^{-1} B_{m_p}\right)$$

onMRAC+ Additional Update Law (disturbance term)

$$\dot{\hat{\sigma}}_p = \frac{\Gamma_{\sigma_\mathrm{p}}}{1 + R_{\sigma_p} p^2}\left(e_p P_q B_{m_q} + \nu_{\sigma_q} \hat{\sigma}_p B_{m_p}^T P_p A_{m_p}^{-1} B_{m_p}\right)$$

Pitch Axis

note: 50 ms of delay (8 frames) was added to p_m and q_m to account for known system delays and filter-induced phase loss on p and q feedbacks.

$$e_q(t) = \begin{bmatrix} \int q_m(t) - \int q(t) \\ q_m(t) - q(t) \end{bmatrix}$$

$$\begin{bmatrix} \dot{\hat{\theta}}_{q1} \\ \dot{\hat{\theta}}_{q2} \end{bmatrix} = \begin{bmatrix} \Gamma_{\mathrm{q}1} & 0 \\ 0 & \Gamma_{\mathrm{q}2} \end{bmatrix} e_q^T P_q B_{m_q} x_q$$

note: $\Gamma_{\mathrm{q}1} \approx 0$, $\hat{\sigma}_q = 0$

$$\begin{bmatrix} \dot{\hat{\theta}}_{q1} \\ \dot{\hat{\theta}}_{q2} \end{bmatrix} = \frac{\begin{bmatrix} \Gamma_{\mathrm{q}1} & 0 \\ 0 & \Gamma_{\mathrm{q}2} \end{bmatrix}}{1 + x_q^T R_{\theta_q} x_q}\left(e_q^T P_q B_{m_q} x_q + x_q \nu_{\theta_q} x_q^T \begin{bmatrix} \hat{\theta}_{q1} \\ \hat{\theta}_{q2} \end{bmatrix} B_{m_q}^T P_q A_{m_q}^{-1} B_{m_q}\right)$$

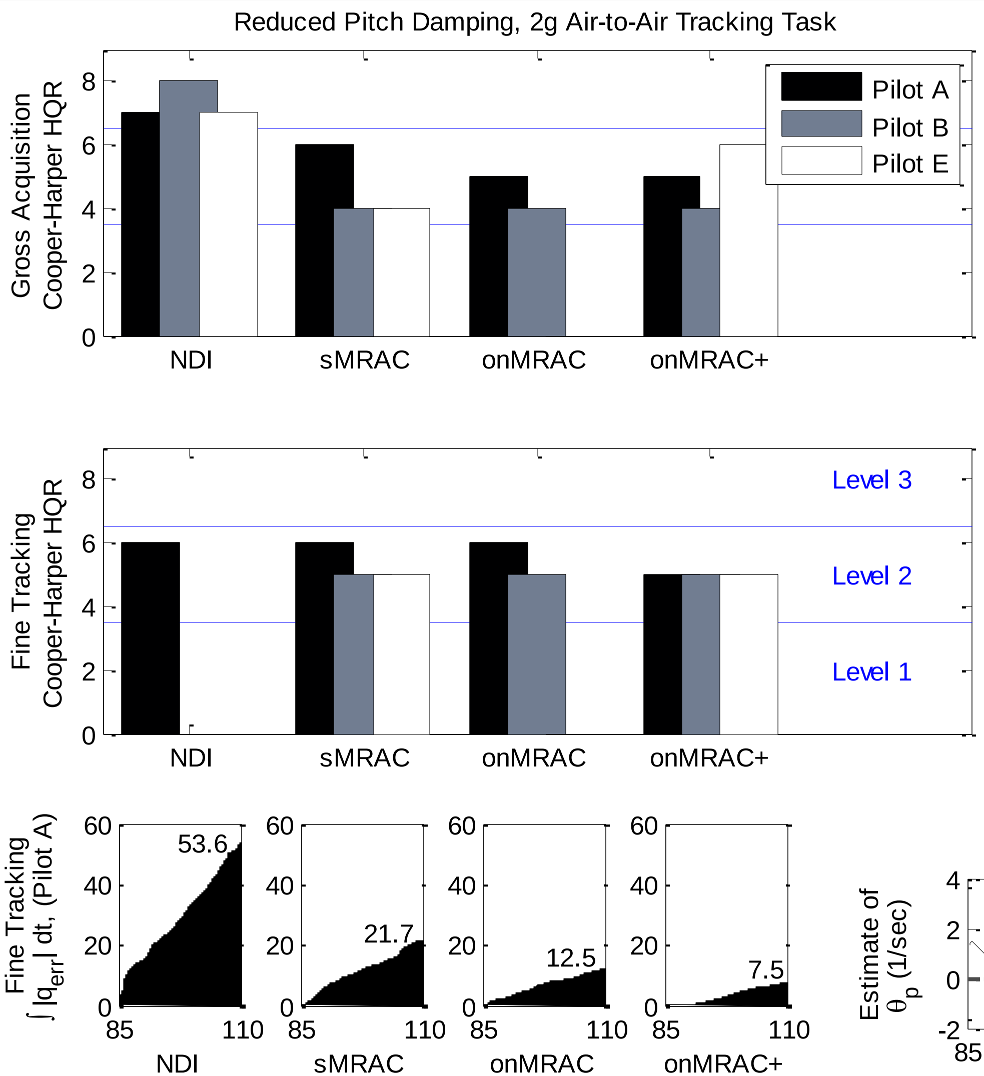
note: $\Gamma_{\mathrm{q}1} \approx 0$, $\hat{\sigma}_q = 0$

$$\dot{\hat{\sigma}}_q = \frac{\Gamma_{\sigma_\mathrm{q}}}{1 + x_q^T R_{\sigma_q} x_q}\left(e_q^T P_q B_{m_q}\right)$$

Simulated In-Flight Failures

Simulated Failure	Magnitude
1. Reduced pitch damping	80% reduction
2. Reduced roll damping	117% reduction
3. Reduced pitch static stability	60% reduction
4. Frozen left stabilator	100% failed
5. Roll-to-pitch input coupling	100% of pilot roll stick added to pilot pitch stick

Flight Data Analysis – Reduced Pitch Damping Failure

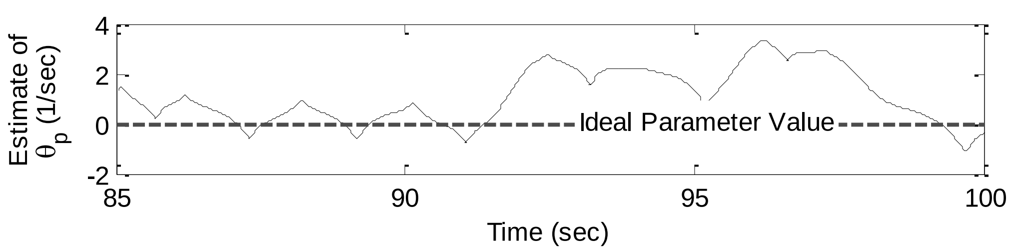


Assessment of Metrics

HQ Ratings do not always correlate well with improvements in reference model tracking… possibly due to **Predictability** and **Workload**.

Example:
With onMRAC, Pilot A reported using <u>extensive compensation</u>.

For this failure the ideal estimate of θ_p is zero, and positive values increase roll sensitivity. Midway through the task, the estimate of θ_p grows positive, caused by rudder-stick cross-control.

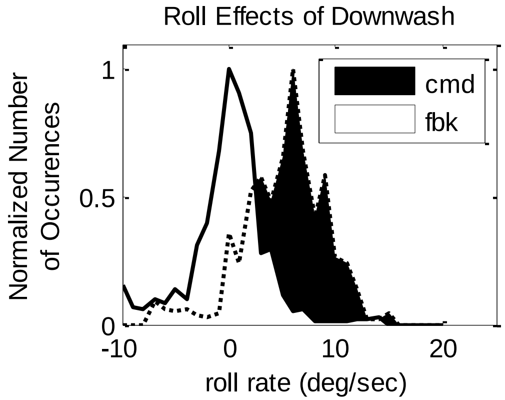


Flight Data Analysis – Reduced Roll Damping Failure

Roll-Axis "HAL-IO" (onMRAC) 

"… so was that the weights doing that or was that the wake vortex?"

The answer: A little bit of both – the pilot applied roll stick to trim out wake effects, causing the roll-axis adaptive parameter to switch signs.

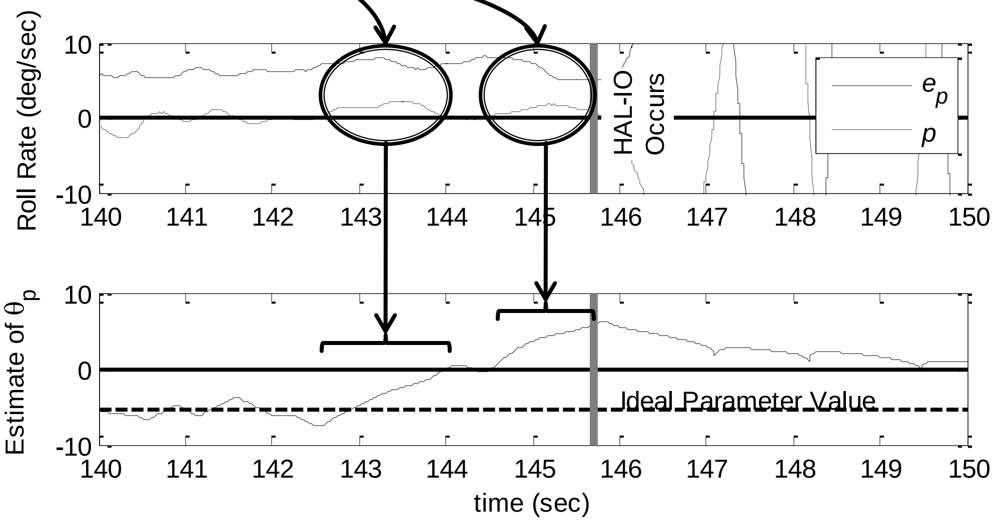


The OCM and normalization terms depend on p^2. When p is small positive and e_p is large positive, the adaptive parameter grows quickly, away from its ideal value.

$$\dot{\hat{\theta}}_p = \frac{\Gamma_p}{1 + R_{\theta_p} p^2}\left(e_p P_q B_{m_q} p + \nu_{\theta_q} p^2 \hat{\theta}_p B_{m_p}^T P_p A_{m_p}^{-1} B_{m_p}\right)$$

Roll sensitivity develops as the errant adaptation reduces roll damping even further than the original failure.

Note: during the HAL-IO, the OCM term drives the adaptive parameter back toward zero.



Adverse Effects of Quasi-Steady, Non-Zero Pilot Compensation

Steady-Heading Sideslips	Un-commanded rolls occurred in piloted simulation testing… implemented a gain to suppress adaptation with rudder pedal command
2.5g Wind-up Turns with Single Stab Failure	Un-commanded rolls occurred in piloted simulation testing… only occurred with 1 of 5 pilots (the most "steady" of all the pilots)… not fixed
Formation Tracking with Downwash Effects	Increased roll sensitivity occurred in flight testing… discussed on "Reduced Roll Damping" slide
2g Air-to-Air Tracking with Pedal-Stick Cross Control	Increased roll sensitivity occurred in flight testing… discussed on "Reduced Pitch Damping" slide
2g Air-to-Air Tracking with No Failures	Pitch oscillations with constant aft stick found in piloted sim… fixed by high-pass filtering feedback and error signals to the pitch adaptive controller

Flight Data Analysis – Roll-to-Pitch Coupling Failure

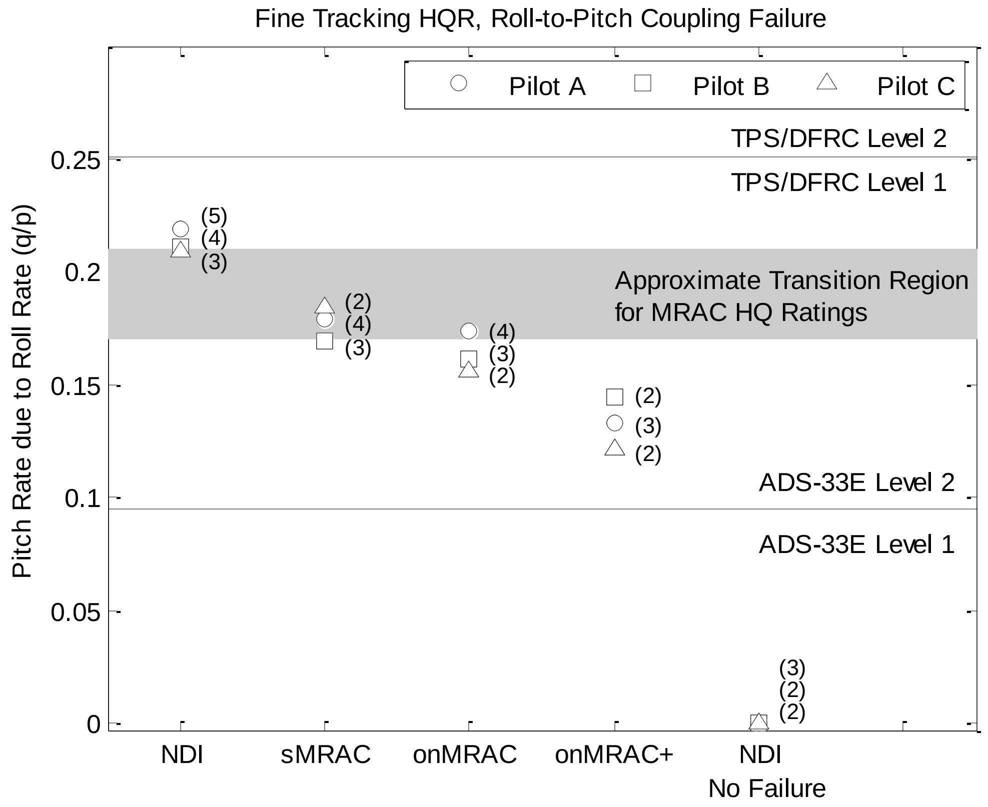
New Cross-Coupling Handling Qualities Metric

The USAF Test Pilot School and NASA Dryden have proposed a new handling qualities prediction metric for fixed wing aircraft with coupling between the pitch and roll axes, based on the ADS-33E metric for rotary wing aircraft.

MRAC Flight Results:
The controller with the exogenous disturbance term (onMRAC+) had the largest reduction in coupling. It was rated the same as the un-failed aircraft, an improvement from Level 2 to Level 1 (2 HQR points).

The other adaptive controllers showed slightly less improvement (1 HQR point).

Reaction to coupling seems to be very pilot dependent, with one pilot rating all four configurations as Level 1.



Lessons Learned (preliminary)

Complexity:

<u>sMRAC</u>

- no glaring faults, such as over-adaptation, bursting
- in general, exhibited reduced tracking performance but improved predictability

<u>onMRAC and onMRAC+</u>

- not surprisingly, these controllers seem to have both benefits and drawbacks
- further analysis may show how to keep the benefits and eliminate the drawbacks

<u>Summary</u>

These types of simple adaptive controllers can be effective for at least some classes of failures.

Parameter Tuning:

<u>Failure Type (easiest)</u>

Scenarios without uncertainty and with matched uncertainties make good touchstone cases because the ideal parameter values are known. Un-matched and disturbance cases make good stress cases.

<u>Maneuver Type</u>

A tuning process based around doublets is insufficient. More complex maneuvers are often poorly represented by linearized plant models.

<u>Pilot Technique (most difficult)</u>

The pilot may (unknowingly) employ control techniques that the designer did not anticipate. This is especially true for failed aircraft. The smooth pilot is as important a stress case as the aggressive pilot.

<u>Metrics</u>

For piloted aircraft, pilot comments are by far the best metric.