L_1 Adaptive Control and Its Transition to Practice

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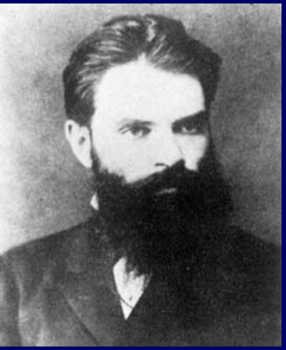
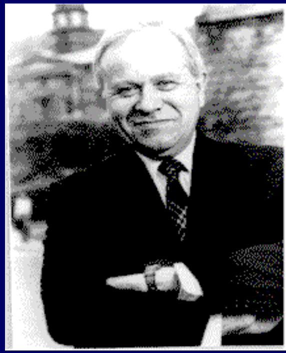


A. M. Lyapunov
1857-1918



G. Zames
1934-1997

Outline

- Historical Overview
- V&V Challenge of Adaptive Control
- Certification of Advanced FCS
- Speed of Adaptation, Performance, Robustness
- Separation between Adaptation and Robustness
- Overview of Aerospace Applications
- Flight Tests of Piloted Aircraft
- Conclusions, summary and future work

Motivation

- **Early 1950s – design of autopilots operating at a wide range of altitudes and speeds**
  - ➔ Fixed gain controller did not suffice for all conditions
    - ➔ Gain scheduling for various conditions
  - ➔ Several schemes for self-adjustment of controller parameters
    - ➔ Sensitivity rule, MIT rule
  - ➔ **1958, R. Kalman, self-tuning controller**
    - ➔ **Optimal LQR with explicit identification of parameters**

- **1950-1960 - flight tests X-15 (NASA, USAF, US Navy)**
  - ➔ bridge the gap between manned flight in the atmosphere and space flight
  - ➔ Mach 4 - 6, at altitudes above 30,500 meters (100,000 feet)
  - ➔ 199 flights beginning June 8, 1959 and ending October 24, 1968
  - ➔ November 15, 1967, X-15A-3

First Flight Test in 1967

The Crash of the X-15A-3 (November 15, 1967)

X-15A-3 on its B52 mothership

X-15A-3

Crash due to stable, albeit non-robust adaptive controller!

"*Brave Era*", *a la K. Astrom*, 1985

Crash site of X-15A-3

Historical Background

- ➢ Sensitivity Method, MIT Rule, Limited Stability Analysis (1960s)
  - ⇨ Whitaker, Kalman, Parks, et al.
- ➢ Lyapunov based, Passivity based (1970s)
  - ⇨ Morse, Narendra, Landau, et al.
- ➢ Global Stability proofs (1970-1980s)
  - ⇨ Astrom, Morse, Narendra, Landau, Goodwin, Keisselmeier, Anderson, et al.
- ➢ Robustness issues, instability (early 1980s)
  - ⇨ Rohrs, Valavani, Athans, Marino, Tomei, Egard, Ioannou, Anderson, Sastry, et al.
- ➢ Robust Adaptive Control (1980s)
  - ⇨ Ioannou, Sun, Praly, Jiang, Tsakalis, Sun, Tao, Datta, Middleton, Basar, et al.
- ➢ Nonlinear Adaptive Control (1990s)
  - ➢ Adaptive Backstepping, Neuro, Fuzzy Adaptive Control
    - ⇨ Krstic, Kanelakopoulos, Kokotovic, Bernstein, Ioannou, Lewis, Farrell, Polycarpou, Kosmatopoulos, Xu, Wang, Christodoulou, Rovithakis, et al.
- ➢ Search methods, multiple models, switching techniques (1990s)
  - ⇨ Morse, Martenson, Miller, Barmish, Narendra, Anderson, Safonov, Hespanha, et al

Landmark Achievement: Adaptive Control in Transition

- **Air Force programs: RESTORE (**X-36 unstable tailless aircraft **1997), JDAM (late 1990s, early 2000s)**
  - ➔ Demonstrated that there is no need for wind tunnel testing for determination of aerodynamic coefficients
    - ✓(an estimate for the wind tunnel tests is **8-10mln dollars at Boeing**)

Lessons Learned: limited to slowly-varying uncertainties, lack of transient characterization

- Fast adaptation leads to high-frequency oscillations in control signal, reduces the tolerance to time-delay in input/output channels
- Determination of the "best rate of adaptation" heavily relies on "expensive" Monte-Carlo runs

Boeing question: How fast to adapt to be robust?

L_1 Adaptive Control

☐ Main features:

- guaranteed fast adaptation
- decoupling between adaptation and robustness
- guaranteed transient performance
  - **NOT** achieved via persistency of excitation, control reconfiguration or gain-scheduling!
- guaranteed **time-delay margin**

- performance limitations reduced to hardware limitations

- uniform scaled transient response dependent on changes in
  - initial condition
  - value of the unknown parameter
  - reference input

- Suitable for development of theoretically justified Verification & Validation tools for feedback systems

Key feature – feasibility of the control objective

- **System:** $\dot{x}(t) = A_m x(t) \; + \; b\left(u + \theta^\top(t)x(t)\right) \; , \quad x(0) = x_0$

- Nominal controller in MRAC: $u_{\mathrm{MRAC}}(t) = -\theta^\top(t)x(t) \; + \; k_g r(t)$
- Desired Reference System:

$$\dot{x}_{\mathrm{des}}(t) = A_m x_{\mathrm{des}}(t) \; + \; b k_g r(t)$$

Overly ambitious goal

- Nominal controller in L$_1$: $u_{\mathcal{L}_1}(t) = C(s)\left\{-\theta^\top(t)x(t) \; + \; k_g r(t)\right\}$
- Achievable reference system:

$$\dot{x}_{\mathrm{ref}}(t) = A_m x_{\mathrm{ref}}(t) \; + b\Big((1 - C(s))\left\{\theta^\top(t)x_{\mathrm{ref}}(t)\right\} \; + \; C(s)\left\{k_g r(t)\right\}\Big)$$

- Sufficient condition for stability:

$$\left\|(1 - C(s))\,(s\mathbb{I} - A_m)^{-1} b\right\|_{\mathcal{L}_1} < \frac{1}{L} \qquad \Rightarrow \qquad \|x_{\mathrm{ref}}\|_{\mathcal{L}_\infty} < \infty$$

Result: Decoupling of identification from control leads to guaranteed robustness in the presence of fast adaptation!

Red Flags Raised in Literature

The notion of having a flag in an adaptive control algorithm to indicate the inappropriateness of an originally posed objective is practically important, and missing from older adaptive control literature. Logic really demands it. If a plant is initially unknown or only partially unknown, a designer may not know a priori that a proposed design objective is or is not practically obtainable for the plant.

``…It is clear that the identification time scale needs to be faster than the plant variation time scale, else identification cannot keep up. It also turns out that it is harder to develop good adaptive controllers, which identify (and thus adjust the controllers) at a time scale comparable with that of the closed--loop dynamics. Interaction of the two processes can occur and generate instability."

*Brian Anderson, **"Failures of Adaptive Control Theory",** COMMUNICATIONS IN INFORMATION AND SYSTEMS, Vol. 5, No. 1, pp. 1-20, 2005*
- *Dedicated to Prof. Thomas Kailath on his 70th Birthday*

1. Fekri, Athans, and Pascoal, "Issues, Progress and New Results in Robust Adaptive Control", International Journal on Adaptive Control and Signal Processing, March 2006
2. B. Anderson, Challenges of adaptive control: past, permanent and future, Annual Reviews in Control, pages 123-125, December, 2008

Direct and Indirect Methods of Adaptive Control

Direct Method:

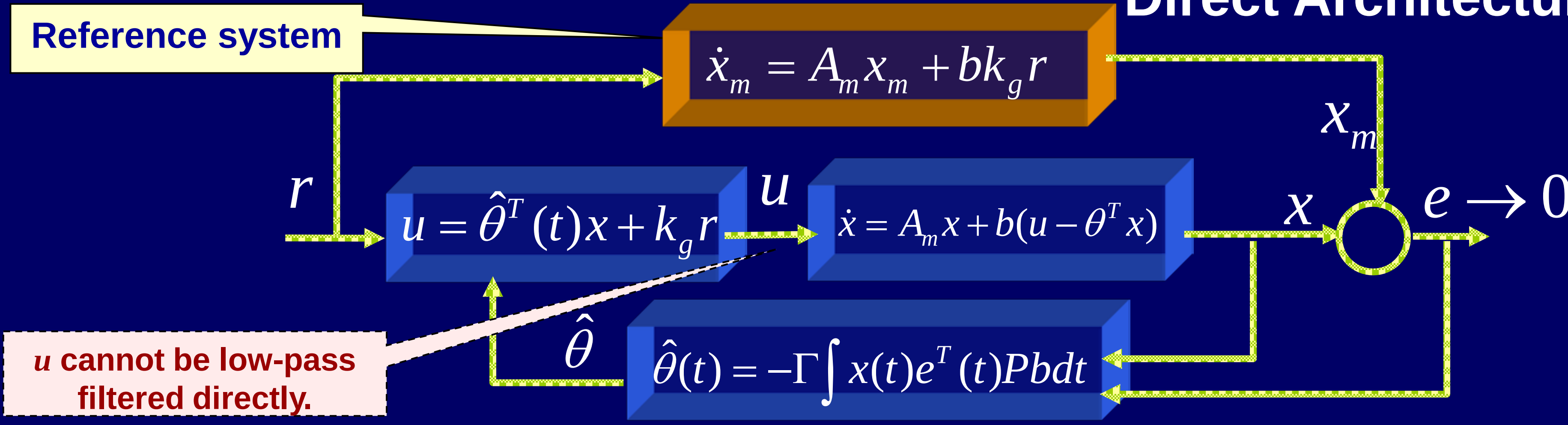
- Estimate the controller parameters
- The <u>stable</u> error dynamics and adaptive laws are derived using the structure of the control signal
- Asymptotic convergence of tracking error is concluded from Barbalat's lemma

Indirect Method:

- Estimate the system parameters
- The <u>stable</u> error dynamics and adaptive laws are derived <u>independent</u> of the control signal
- The control signal is synthesized using the estimated parameters
- Asymptotic convergence of tracking error is concluded from Barbalat's lemma

Implementation Differences

Direct Architecture



Reference system

$$\dot{x}_m = A_m x_m + b k_g r$$

x_m

r

$$u = \hat{\theta}^T(t)x + k_g r$$

u

$$\dot{x} = A_m x + b(u - \theta^T x)$$

x

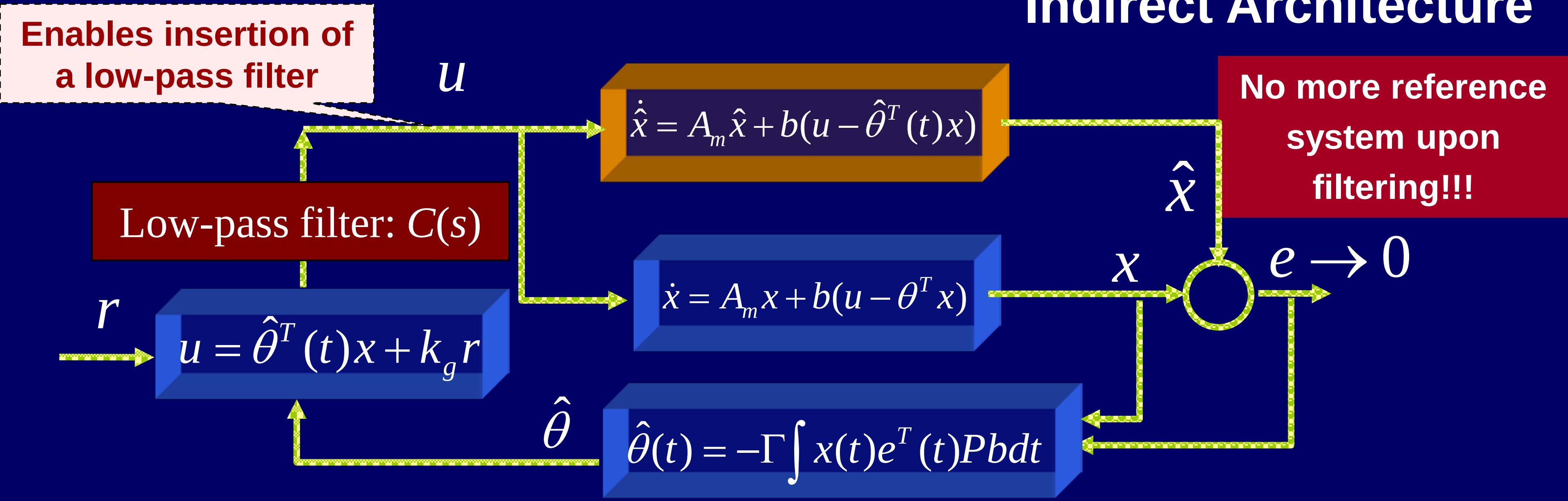
$e \rightarrow 0$

$\hat{\theta}$

$$\hat{\theta}(t) = -\Gamma \int x(t) e^T(t) P b dt$$

u cannot be low-pass filtered directly.

Indirect Architecture



Enables insertion of a low-pass filter

u

$$\dot{\hat{x}} = A_m \hat{x} + b(u - \hat{\theta}^T(t)x)$$

No more reference system upon filtering!!!

$\hat{x}$

Low-pass filter: $C(s)$

$$\dot{x} = A_m x + b(u - \theta^T x)$$

x

$e \rightarrow 0$

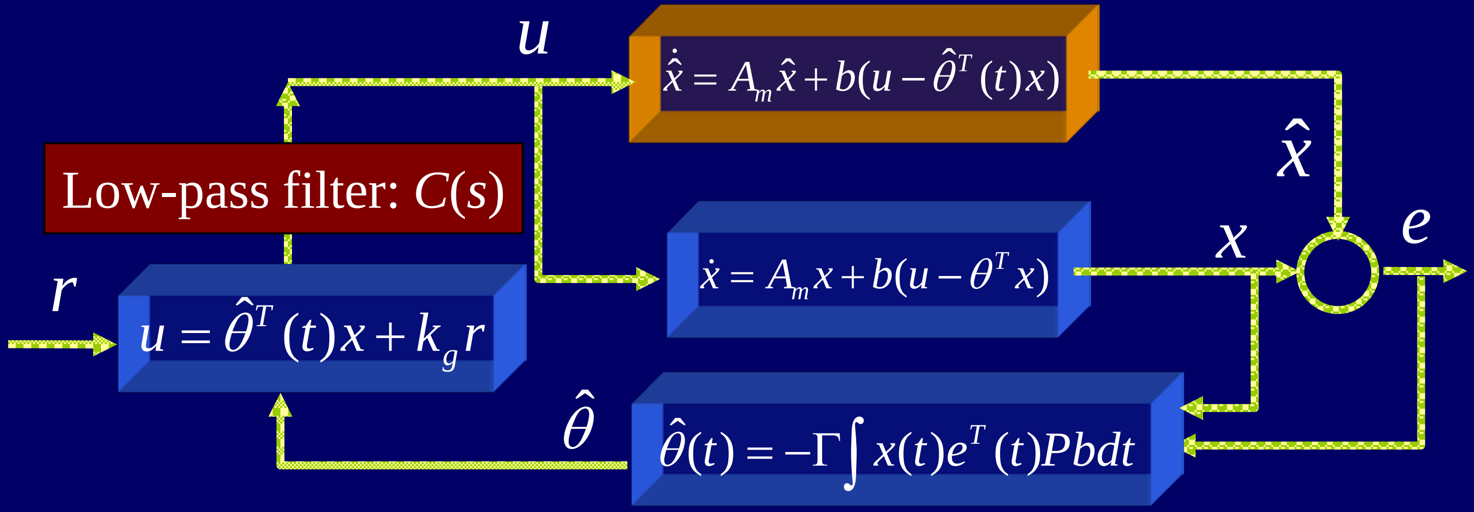
r

$$u = \hat{\theta}^T(t)x + k_g r$$

$\hat{\theta}$

$$\hat{\theta}(t) = -\Gamma \int x(t) e^T(t) P b dt$$

Stability and Asymptotic Convergence



$\dot{\hat{x}} = A_m\hat{x} + b(u - \hat{\theta}^T(t)x)$

Low-pass filter: $C(s)$

$\dot{x} = A_m x + b(u - \theta^T x)$

$u = \hat{\theta}^T(t)x + k_g r$

$\hat{\theta}(t) = -\Gamma\int x(t)e^T(t)Pb\,dt$

- Closed-loop $s\hat{x}(s) = A_m\hat{x}(s) + b\Big((C(s)-1)\{\hat{\theta}^T(t)x(t)\} + C(s)k_g r\Big)$
- Solving: $\hat{x}(s) = \underbrace{(sI - A_m)^{-1}b}_{H_o(s)}\Big((C(s)-1)\Big\{\boxed{\hat{\theta}^T(t)}\big(\hat{x}(t)+\boxed{e(t)}\big)\Big\} + C(s)k_g r\Big)$

bounded

- Sufficient condition for stability via **small-gain theorem**

$$\left\|(1-C(s))(sI-A_m)^{-1}b\right\|_{L_1}\Theta_{\max} \le 1 \quad \Longrightarrow \quad \lim_{t\to\infty}(x(t)-\hat{x}(t)) = 0$$

Barbalat’s lemma

Guaranteed Adaptation Bounds: SCALING

- System state: $\left\| x - x_{ref} \right\|_{L_\infty} \le \frac{\gamma_1}{\sqrt{\Gamma}}$ $\Longrightarrow$ $\boxed{\lim_{\Gamma \to \infty} \left\| x - x_{ref} \right\|_{L_\infty} = 0}$

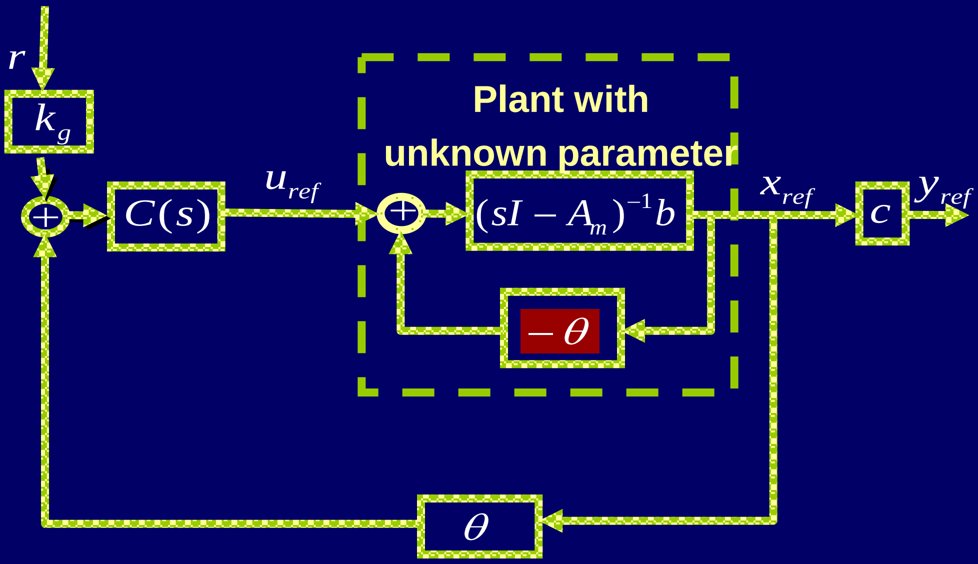
- Control signal: $\left\| u - u_{ref} \right\|_{L_\infty} \le \frac{\gamma_2}{\sqrt{\Gamma}}$ $\Longrightarrow$ $\boxed{\lim_{\Gamma \to \infty} \left\| u - u_{ref} \right\|_{L_\infty} = 0}$

$$\gamma_2 = \left\| C(s) \frac{1}{c_o^\top (sI - A_m)^{-1} b} c_o^\top \right\|_{\mathcal{L}_1} \sqrt{\frac{\bar{\theta}_{\max}}{\lambda_{\max}(P)}} + \left\| C(s) \theta^\top \right\|_{\mathcal{L}_1} \gamma_1 < \infty$$

➔ $C(s) = 1$ (MRAC) $\Longrightarrow$ $\gamma_2 \to \infty$

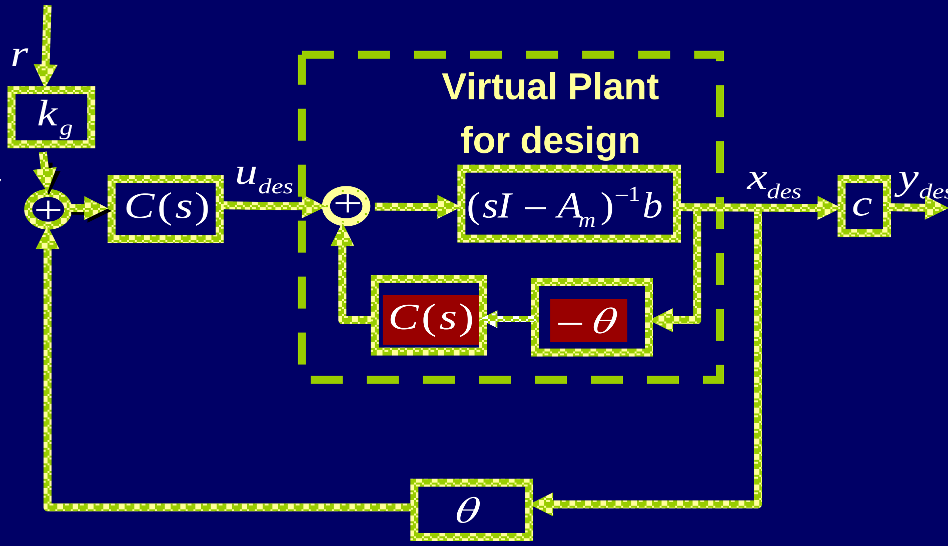
Remark. Non-zero trajectory initialization errors lead to additional additive exponentially decaying terms in the performance bounds.

LTI System for Control Specifications



Reference system

achieved via **fast adaptation**



Design system

for defining the **control specs**

$$y_{ref}(s) = c^T\left(I-(C(s)-1)(sI-A_m)^{-1}b\theta^T\right)^{-1}(sI-A_m)^{-1}bC(s)k_g r(s)$$

$$y_{des}(s) = c^T(sI-A_m)^{-1}bC(s)k_g r(s)$$

Independent of the unknown parameter

Guaranteed Robustness Bounds

$$\left\|y_{ref}-y_{des}\right\|_{L_\infty} \le \frac{\lambda}{1-\lambda}\left\|c^T\right\|_{L_1}\left\|k_g H_o(s)C(s)\right\|_{L_1}\left\|r\right\|_{L_\infty}$$

$$\left\|u_{ref}-u_{des}\right\|_{L_\infty} \le \frac{\lambda}{1-\lambda}\left\|C(s)\theta^T\right\|_{L_1}\left\|k_g H_o(s)C(s)\right\|_{L_1}\left\|r\right\|_{L_\infty}$$

- Sufficient condition for stability

$$\boxed{\lambda=\left\|\left(1-C(s)\right)H_o\left(s\right)\right\|_{L_1}\Theta_{\max}<1}$$

- Performance improvement $\boxed{\lambda \to \min}$

Guaranteed (Uniform and Decoupled) Performance Bounds

- Use large adaptive gain $\boxed{\Gamma_c}$

$$\Rightarrow y(t)-y_{ref}(t)=O\left(\frac{1}{\sqrt{\Gamma_c}}\right),\quad u(t)-u_{ref}(t)=O\left(\frac{1}{\sqrt{\Gamma_c}}\right),\quad \forall t\geq 0$$

- Design $C(s)$ to render $\boxed{\lambda=\left\|\left(1-C(s)\right)H_o(s)\right\|_{L_1}\Theta_{\max}}$ sufficiently small

$$\Rightarrow y_{ref}(t)-y_{des}(t)=O(\lambda),\quad u_{ref}(t)-u_{des}(t)=O(\lambda),\quad \forall t\geq 0$$

Decoupling of adaptation from robustness

$$y(t)-y_{des}(t)=\boxed{O(\lambda)+O\left(\frac{1}{\sqrt{\Gamma_c}}\right)},\quad u(t)-u_{des}(t)=\boxed{O(\lambda)+O\left(\frac{1}{\sqrt{\Gamma_c}}\right)},\quad \boxed{\forall t\geq 0}$$

Large adaptive gain → Smaller step-size → Faster CPU

The sensor and control sampling can be done at a low rate.

Main Result

If $\left\|(1-C(s))H_o(s)\right\|_{L_1}\Theta_{\max}<1$, then the L_1 adaptive controller ensures uniform transient and steady-state performance bounds

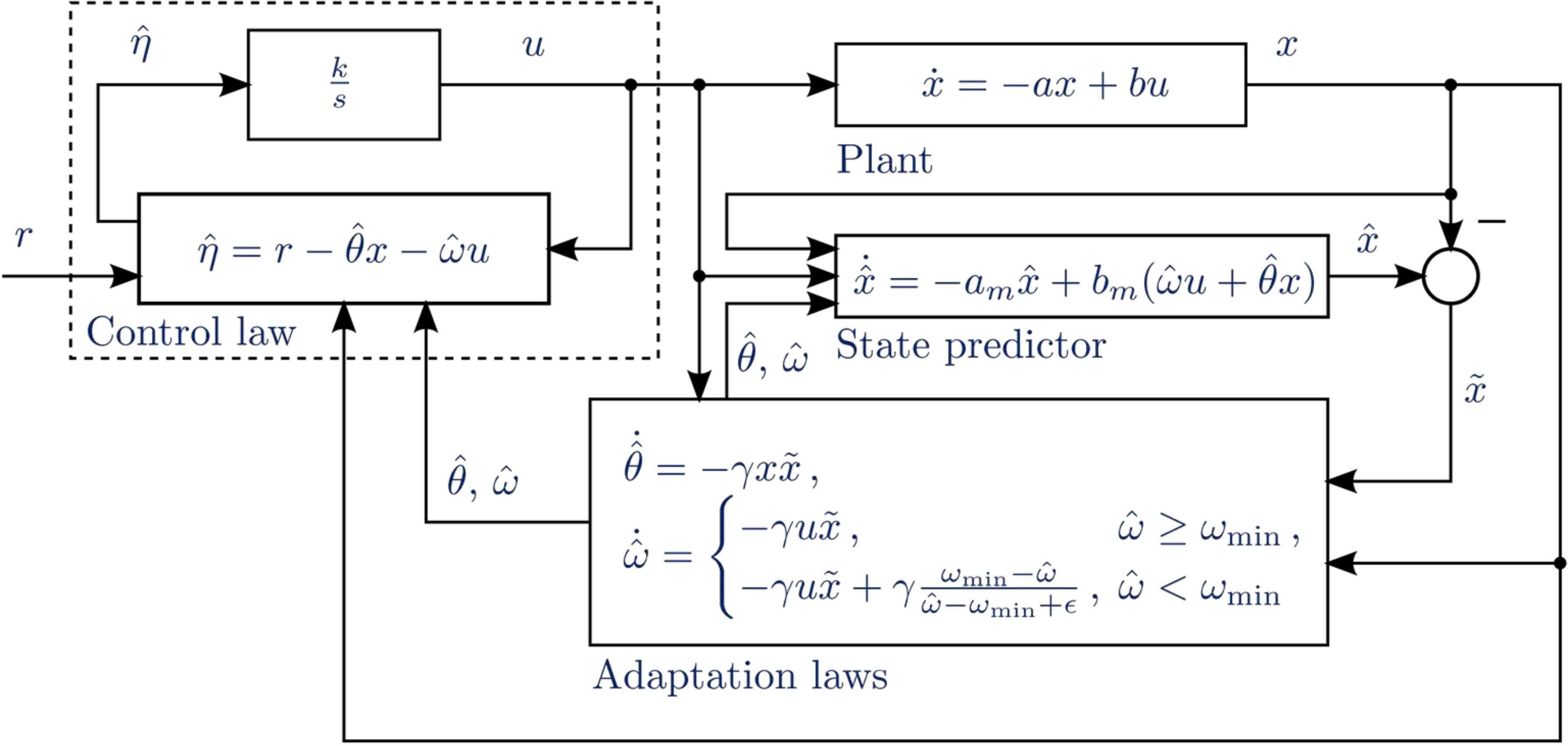
$$\boxed{\left\|u(t)-u_{ref}(t)\right\|_{L_\infty}\approx O\left(\frac{1}{\sqrt{\Gamma}}\right);\quad \left\|x(t)-x_{ref}(t)\right\|_{L_\infty}\approx O\left(\frac{1}{\sqrt{\Gamma}}\right).}$$

Moreover, there exists Γ_0 , such that if $\Gamma>\Gamma_0$, the time-delay margin is guaranteed to stay bounded away from zero

$$\boxed{T_{\text{margin}}\geq T_m>0,}$$

where T_m is the time-delay margin of $H(s)=\dfrac{C(s)\left(1+\theta^T\overline{H}(s)\right)}{1-C(s)}$.
The gain margin can be arbitrarily improved by increasing the domain of projection.

L_1 Adaptive Control in the Presence of Unknown Input Gain



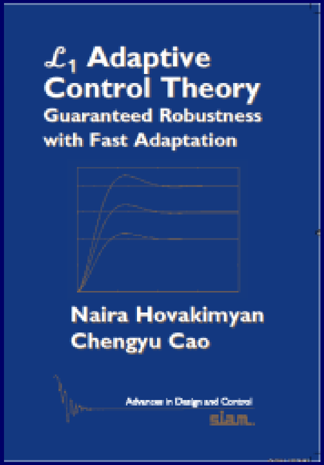
Steady state:

$$\hat{\eta}(t) = r(t) - \hat{\theta}(t)x(t) - \hat{\omega}(t)u(t) = 0$$

$$u(t) = -\frac{\hat{\theta}(t)}{\hat{\omega}(t)}x(t) + \frac{1}{\hat{\omega}(t)}r(t)$$

Recovers indirect MRAC control law

Extensions of the Theory


$\mathcal{L}_1$ Adaptive Control Theory
Guaranteed Robustness with Fast Adaptation

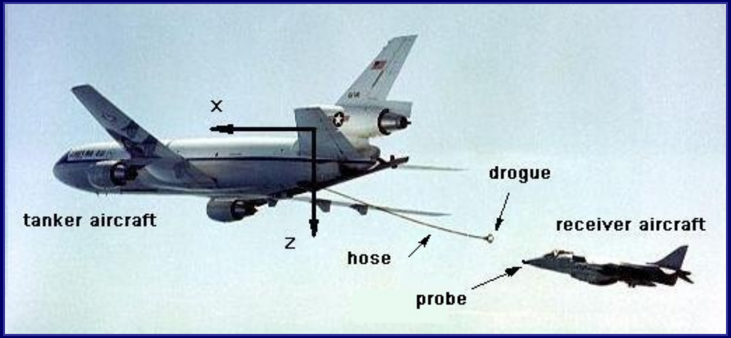
Naira Hovakimyan
Chengyu Cao

Advances in Design and Control
siam

- **State-Feedback:**
  - L_1 Adaptive Control for Systems with TV Parametric Uncertainty and TV Disturbances
  - L_1 Adaptive Control for Systems with Unknown System Input Gain
  - L_1 Adaptive Control for a class of Systems with Unknown Nonlinearities
  - L_1 Adaptive Control for Nonlinear Systems in the presence of Unmodeled Dynamics
  - L_1 Adaptive Control for Systems in the presence of Unmodeled Actuator Dynamics
  - L_1 Adaptive Control for Time-Varying Reference Systems
  - L_1 Adaptive Control for Nonlinear Strict Feedback Systems in the presence of Unmodeled Dynamics
  - L_1 Adaptive Control for Systems with Hysteresis
  - L_1 Adaptive Control for a Class of Systems with Unknown Nonaffine-in-Control Nonlinearities
  - L_1 Adaptive Control for MIMO Systems in the Presence of Unmatched Nonlinear Uncertainties
  - L_1 Adaptive Control in the Presence of Input Quantization
  - L_1 Adaptive Control of Event-triggered Networked Systems

- **Output-Feedback:**
  - L_1 Adaptive Output-Feedback Control for Systems of Unknown Dimension (SPR ref. system)
  - L_1 Adaptive Output-Feedback Control for Non-Strictly Positive Real Reference Systems
  - L_1 Adaptive Control of …..

Aerospace Applications



NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: ED02–0295–5 Date: December 19, 2002 Photo By: Jim Ross

The first X–45A technology demonstrator completed its sixth flight on Dec. 19, 2002, raising its landing gear in flight for the first time.

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: EC87-0182 Date: July 24, 1987 Photo by: NASA

X-29 in Banked Flight

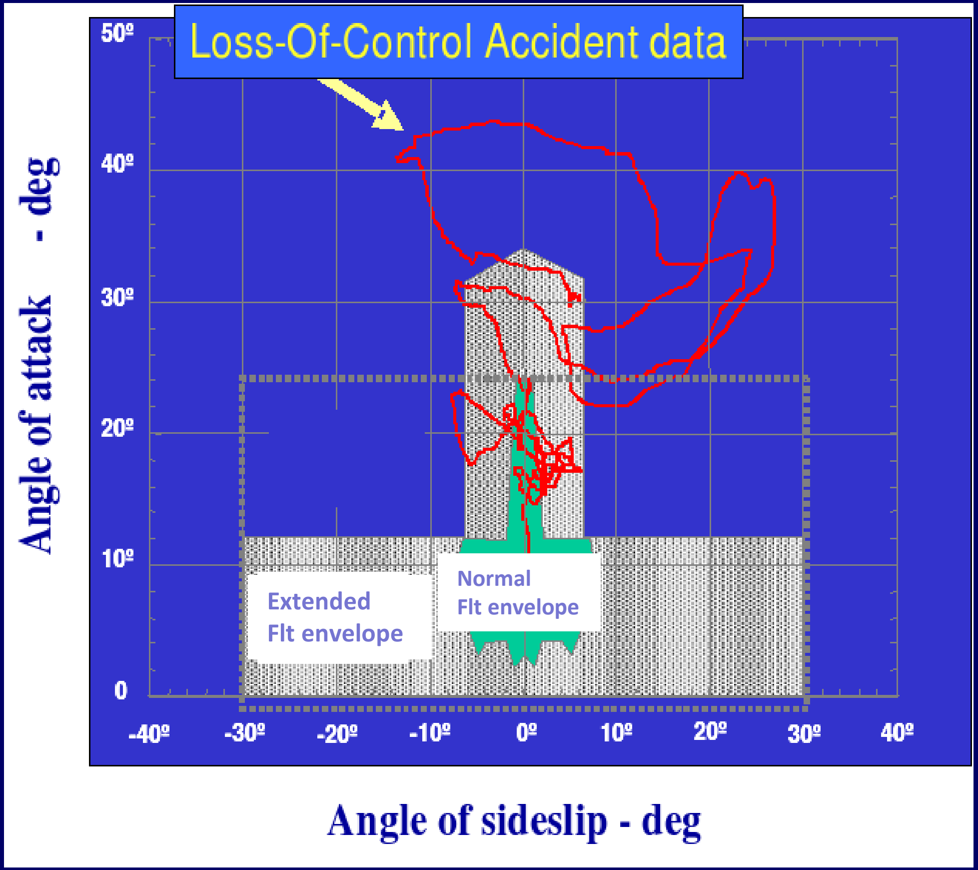
Integrated Resilient Aircraft Control (IRAC)

IRAC research is focused on loss-of-control, failure and damage scenarios, and their mitigation though the application of adaptive control.

Control law objectives:

- Keep aircraft in the **Extended flight envelope**
- Return to **Normal Flight Envelope**

- Control actions within 2-4 seconds of failure onset are **critical**:
  - Need for **transient performance guarantees**
    - **Predictable response**
  - Need for **fast adaptation**



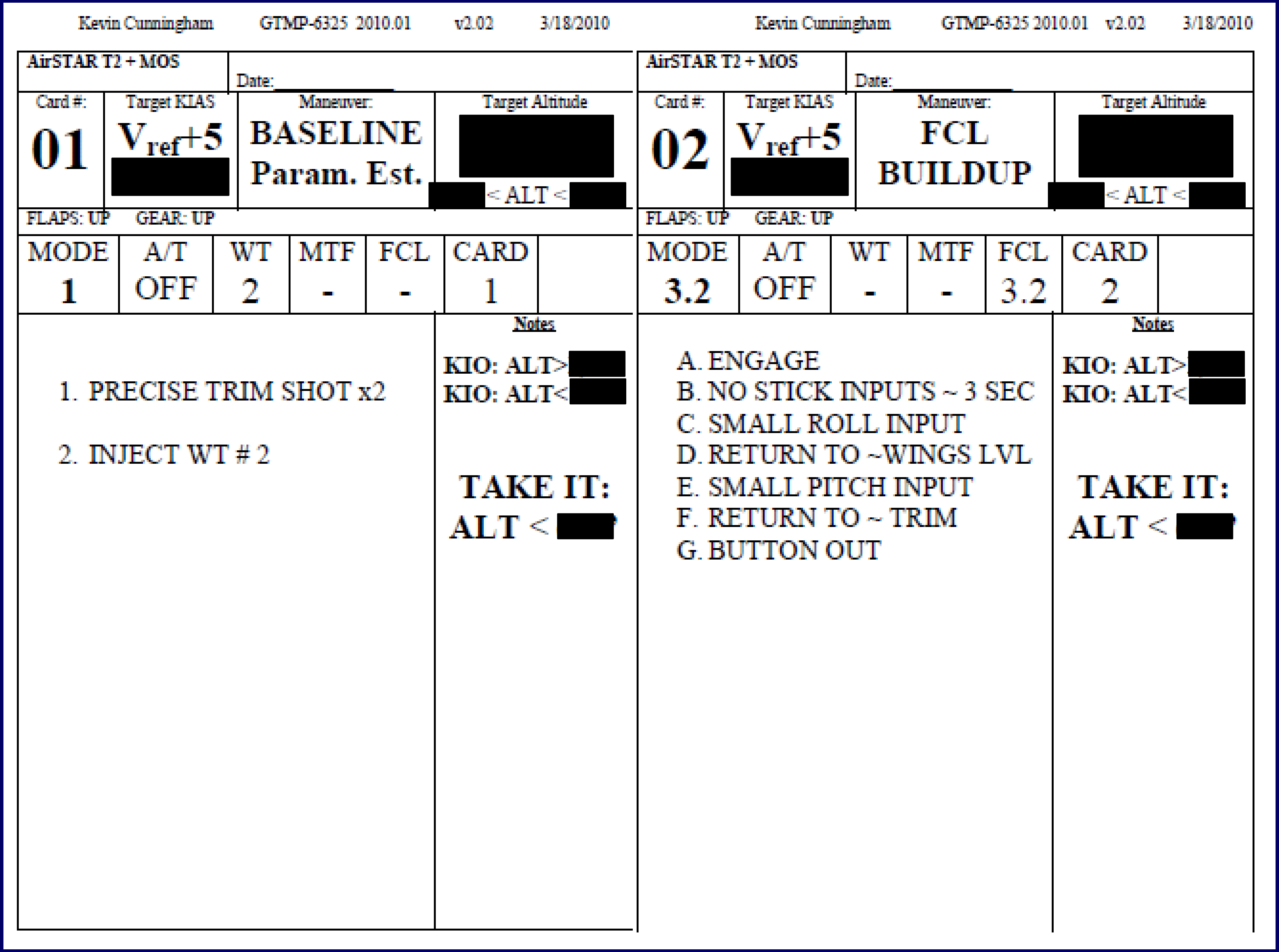
Generic Transport Model

High-risk flight conditions, some unable to be tested in target application environment.

- 5.5 % geometrically and dynamically scaled model
  - 82in wingspan, 96 in length, 49.6 lbs (54 lbs full), 53 mph stall speed
  - Model angular response is 4.26 faster than full scale
  - Model velocity is 4.26 times slower than regular scale

Flight Test Setup : MOS

Flight Test Cards



Kevin Cunningham GTMP-6325 2010.01 v2.02 3/18/2010

AirSTAR T2 + MOS	Date: ________		
Card #: **01**	Target KIAS **V_{ref}+5** [redacted]	Maneuver: **BASELINE Param. Est.**	Target Altitude [redacted] [redacted] < ALT < [redacted]

FLAPS: UP GEAR: UP

MODE	A/T	WT	MTF	FCL	CARD
1	OFF	2	-	-	1

1. PRECISE TRIM SHOT x2
2. INJECT WT # 2

Notes

KIO: ALT> [redacted]
KIO: ALT< [redacted]

TAKE IT:
ALT < [redacted]

Kevin Cunningham GTMP-6325 2010.01 v2.02 3/18/2010

AirSTAR T2 + MOS	Date: ________		
Card #: **02**	Target KIAS **V_{ref}+5** [redacted]	Maneuver: **FCL BUILDUP**	Target Altitude [redacted] [redacted] < ALT < [redacted]

FLAPS: UP GEAR: UP

MODE	A/T	WT	MTF	FCL	CARD
3.2	OFF	-	-	3.2	2

A. ENGAGE
B. NO STICK INPUTS ~ 3 SEC
C. SMALL ROLL INPUT
D. RETURN TO ~WINGS LVL
E. SMALL PITCH INPUT
F. RETURN TO ~ TRIM
G. BUTTON OUT

Notes

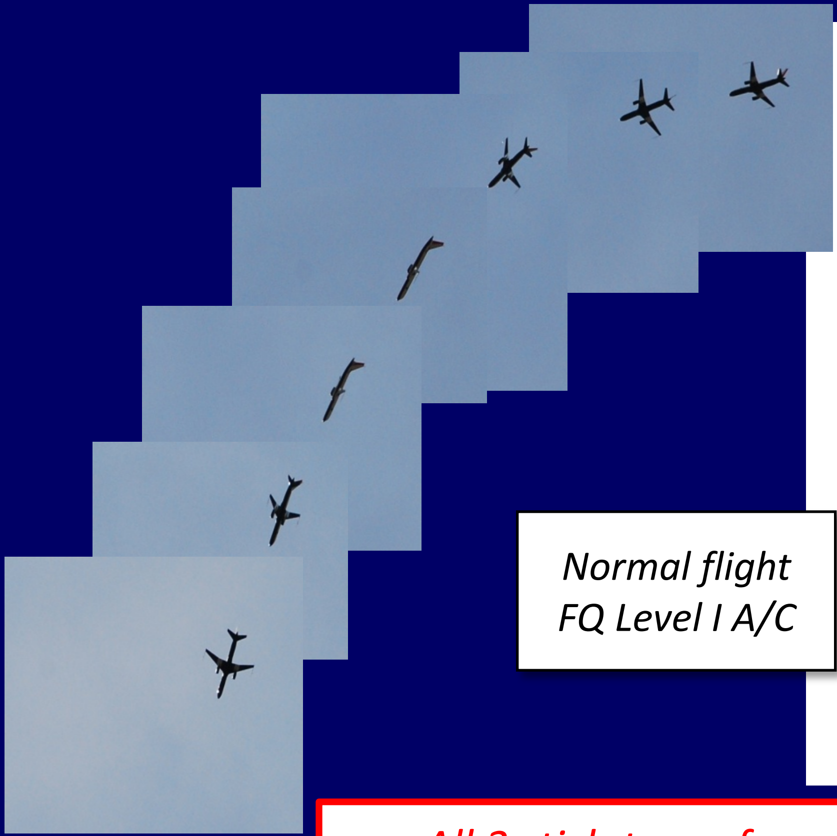
KIO: ALT> [redacted]
KIO: ALT< [redacted]

TAKE IT:
ALT < [redacted]

GTM T2 :: Flight Test Evaluation (June 2010)

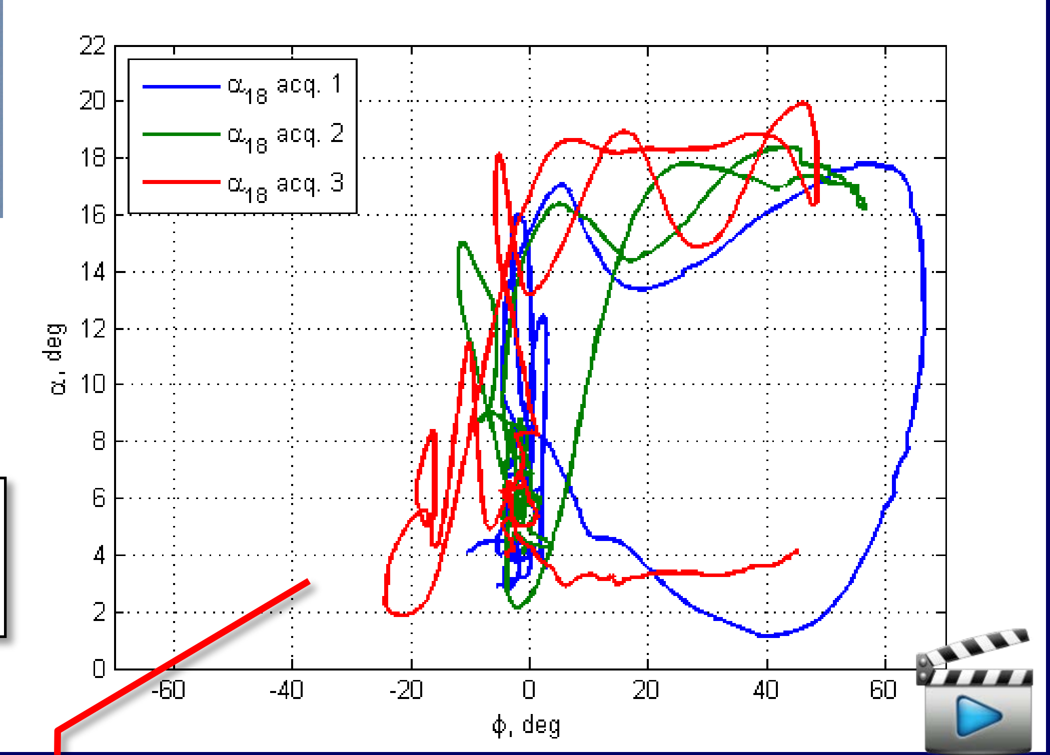
Post-stall, high angle of attack flight

- **Open-loop aircraft** tends to aggressively **roll off** between 13deg and 15deg AOA and exhibits significant degradation in pitch stability



Normal flight
FQ Level I A/C

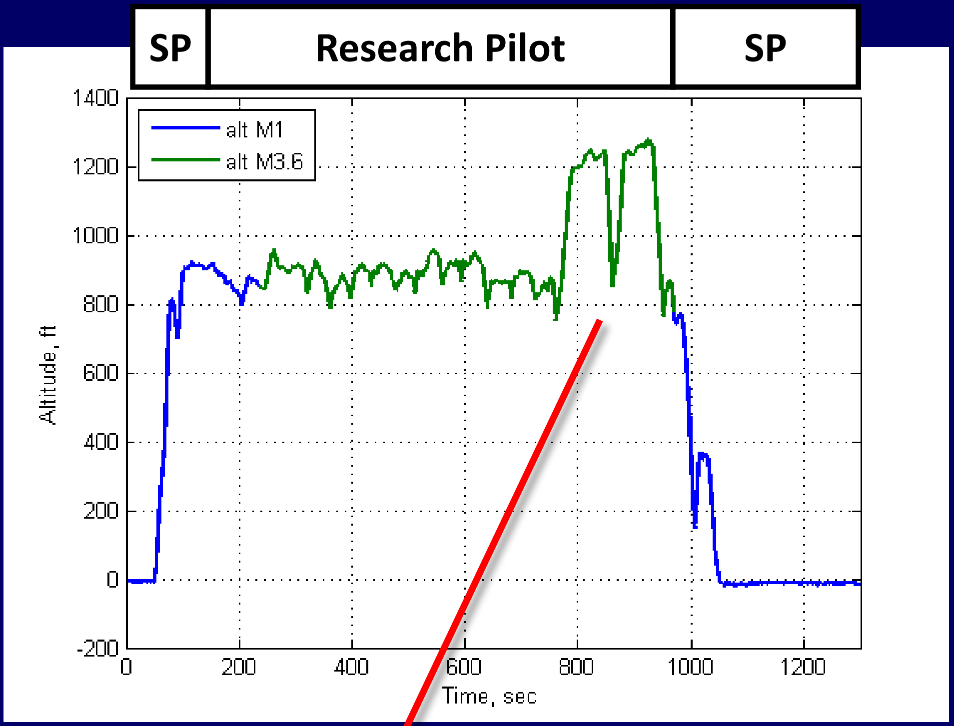
Stick to surface



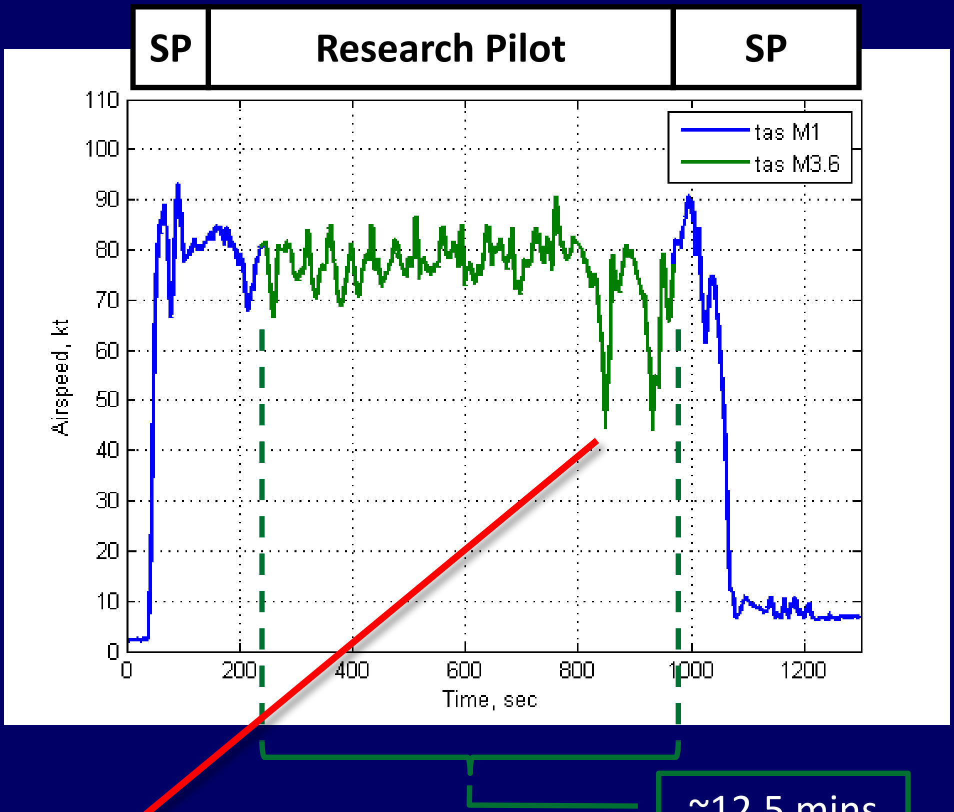
*All 3 stick-to-surface attempts in maintaining controller flight at AOA=18deg were **unsuccessful***

GTM T2 :: Flight Test Evaluation in Post-Stall

- FLT23: Mode 3.6 (L1 all-adaptive) FCL under light turbulence



High AOA flight



Post-stall regimes

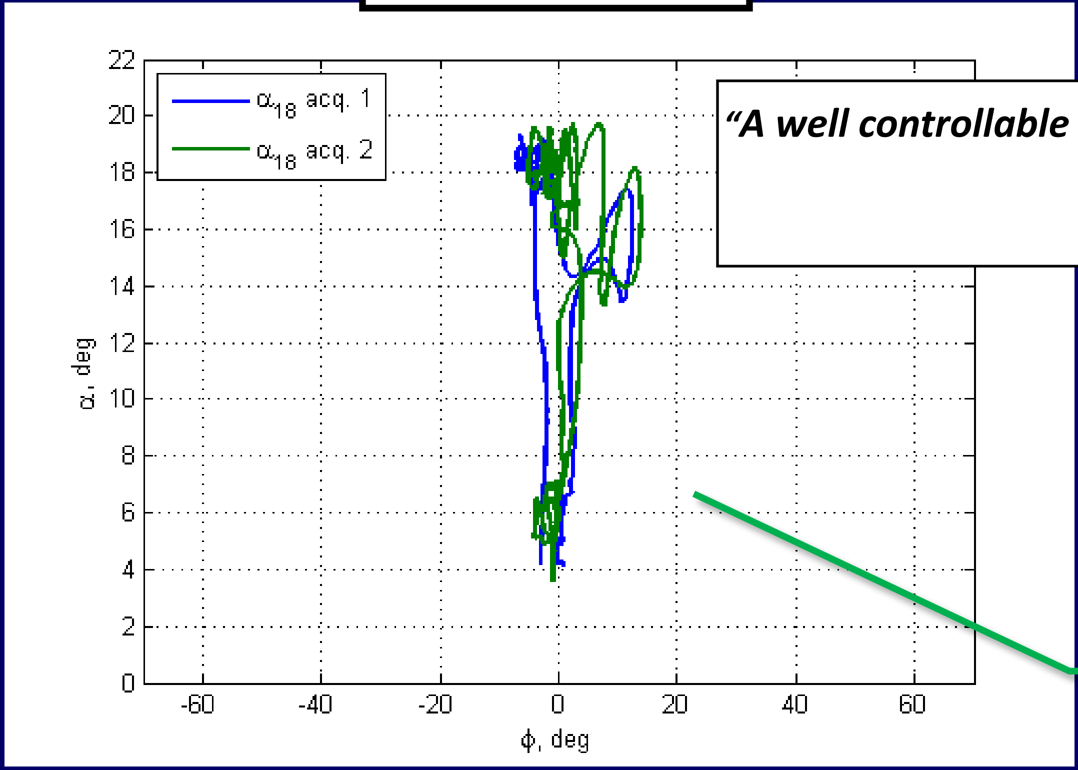
~12.5 mins of flight with L1

GTM T2 :: Repeatable Results in Post-Stall Flight

Post-stall, high angle of attack flight

- **L1 provides departure resilient control for aircraft in post-stall flight**
  - ✓ L1 adaptive controller achieved a very well controlled aircraft (pilot assessment)

L1 AFCS



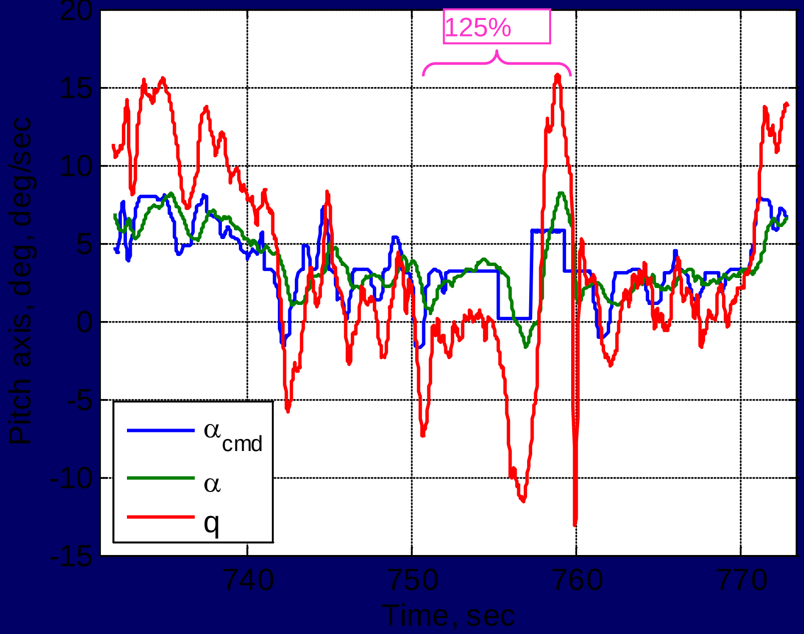
> ***"A well controllable aircraft during stall and post-stall flight"***
>
> *Dan Murri*
>
> *AirSTAR GTM T2 research pilot*

Repeatable results

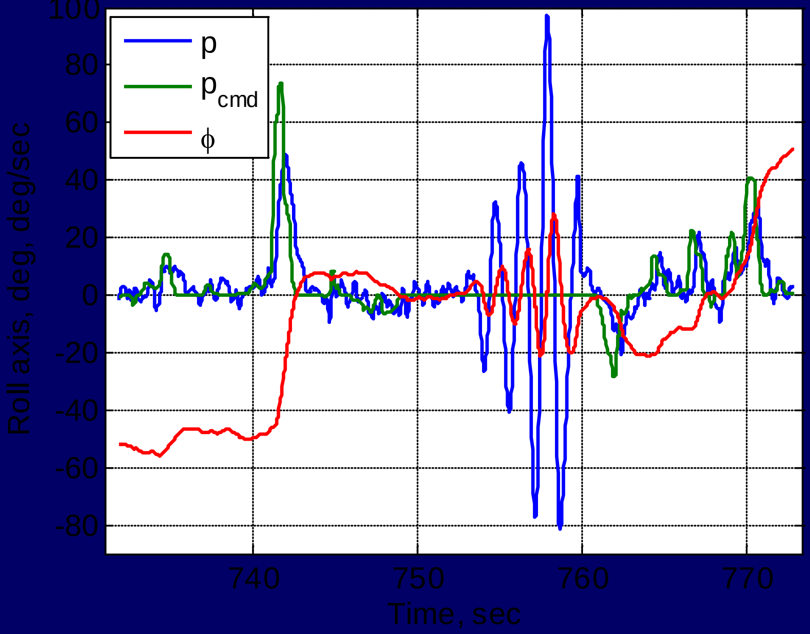
Two AOA=18deg acquisitions
with L1 AFCS

125%Cmα/Clp Degradation WT Response (June 2010)

Pitch axis – α_cmd doublet



Roll axis response

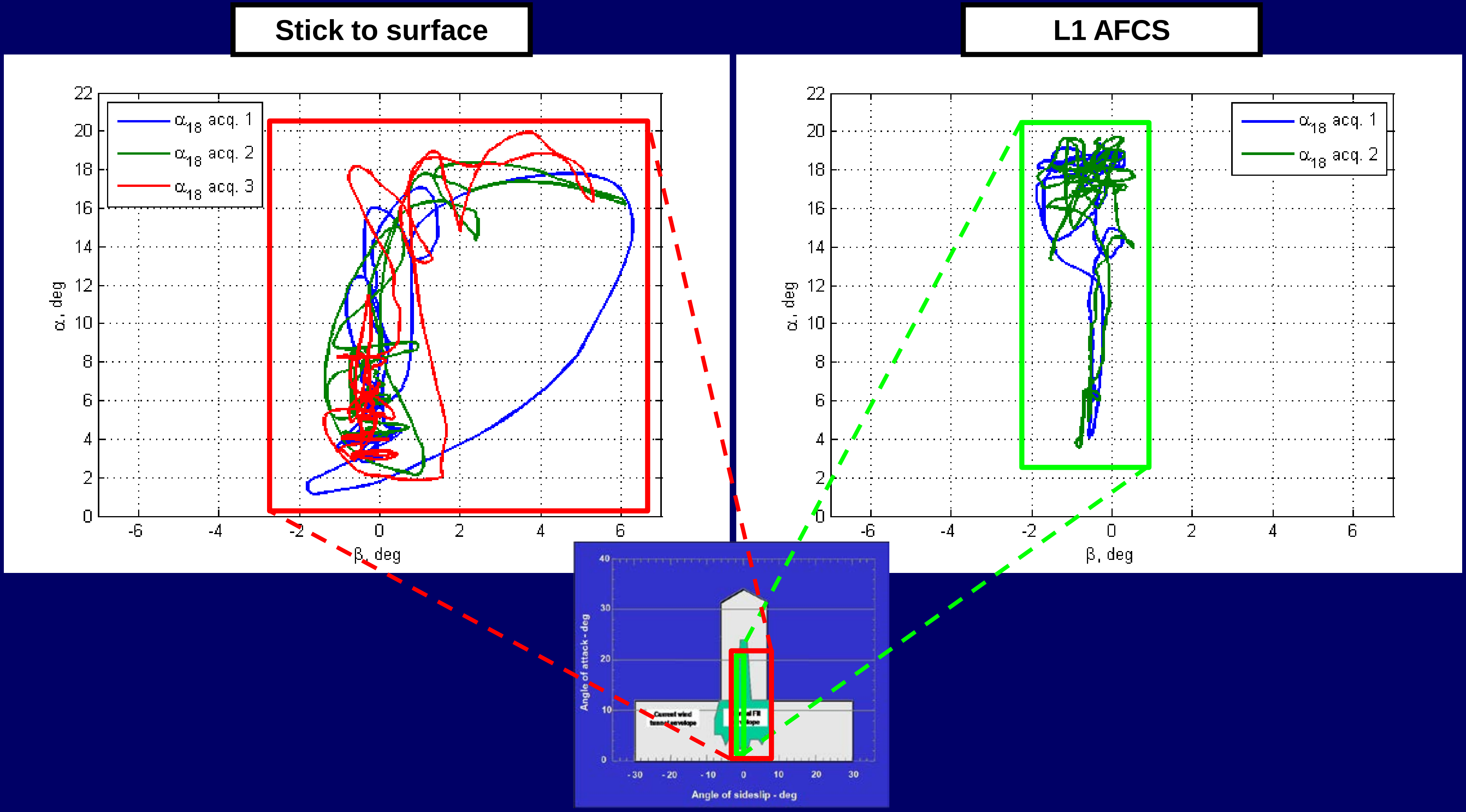


- Pilot called “knock it off”, but did not abandon the control law
- Test engineer simply flipped the switch to turn off the stability degradation fault, and the controller recovered its nominal performance immediately.
- The pilot proceeded to fly into a typical aggressive turn less than 10 seconds after the fault was terminated, **without any corrective action** (~ 770 seconds)
- **The design was done for 147msec time-delay margin, some of which can be traded off for performance recovery (flight test planned for September 2010)**

GTM T2 :: Summary of Flight Test Evaluation (June 2010)

Post-stall, high angle of attack flight

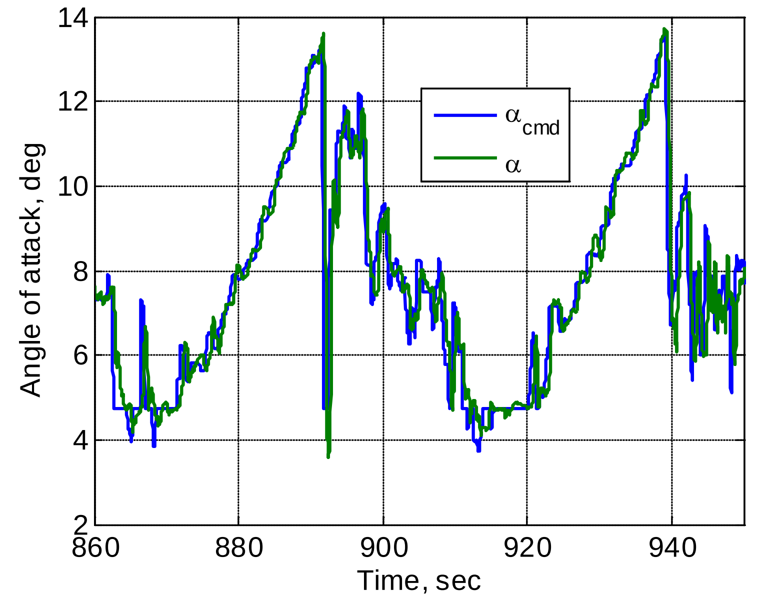
- **L1 provides departure resilient control for aircraft in post-stall flight**

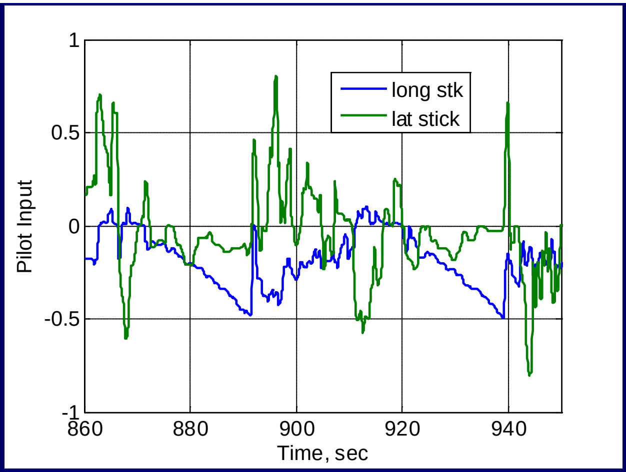


GTM T2 :: Flight Test Evaluation (September 2010)

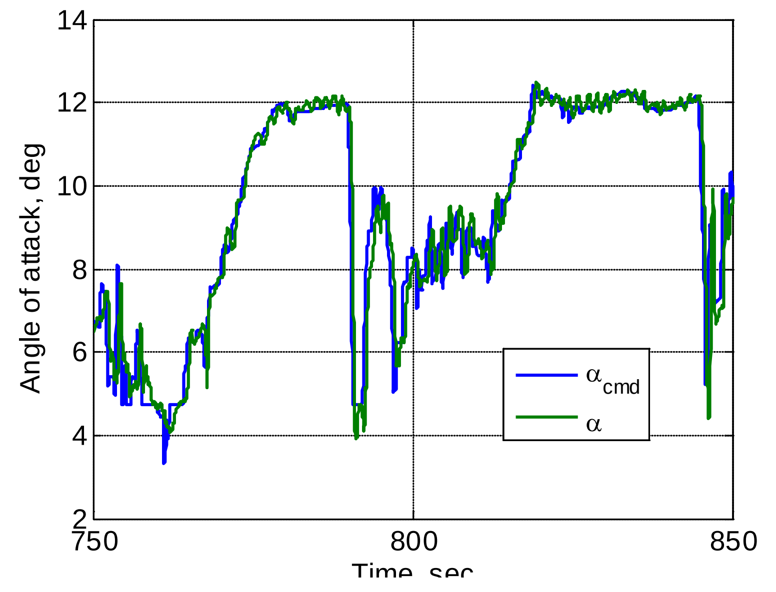
Angle of Attack Vane Calibration: Stall occurs between 12 and 13 degrees

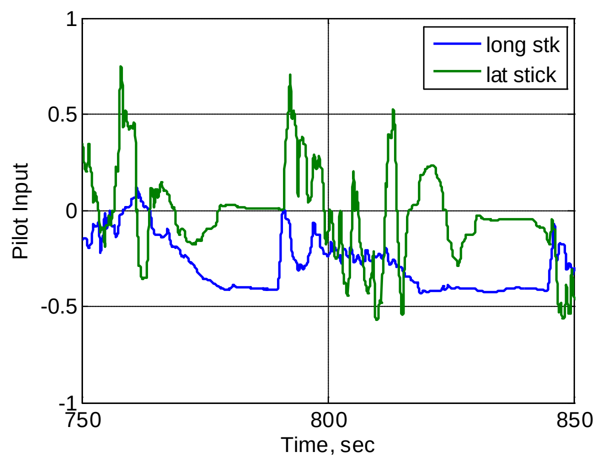
Variable AoA Strategy





Constant AoA Strategy

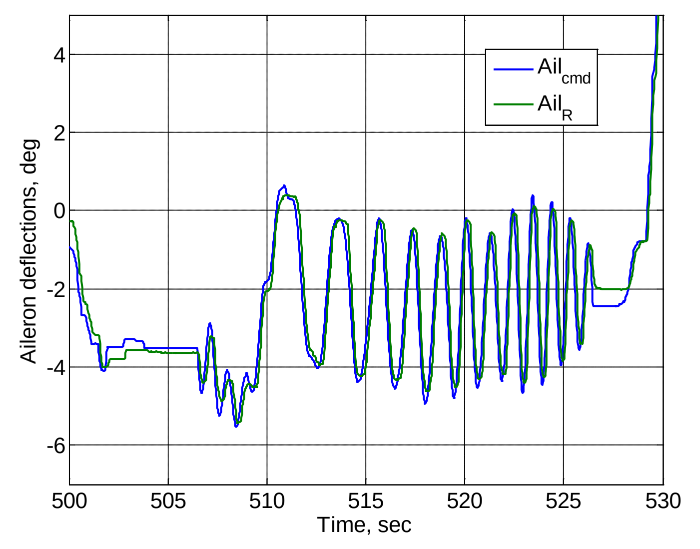


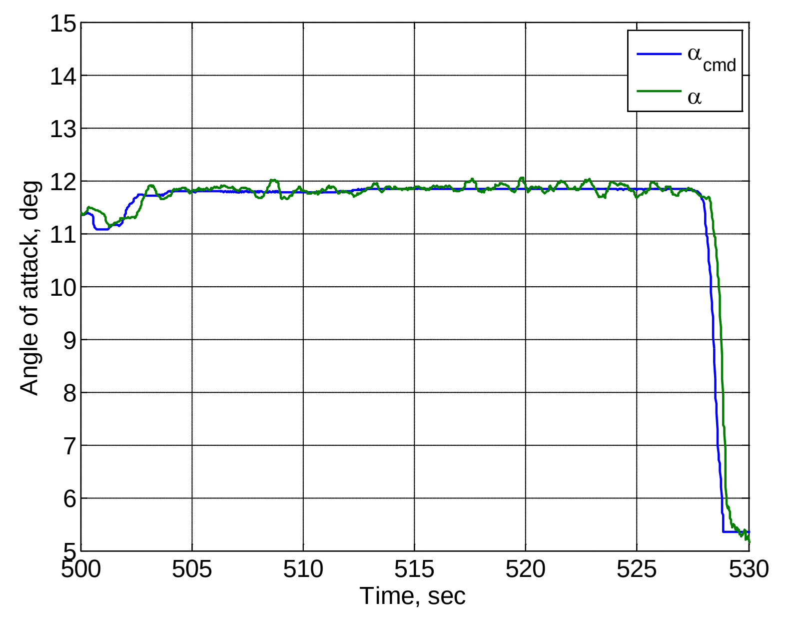


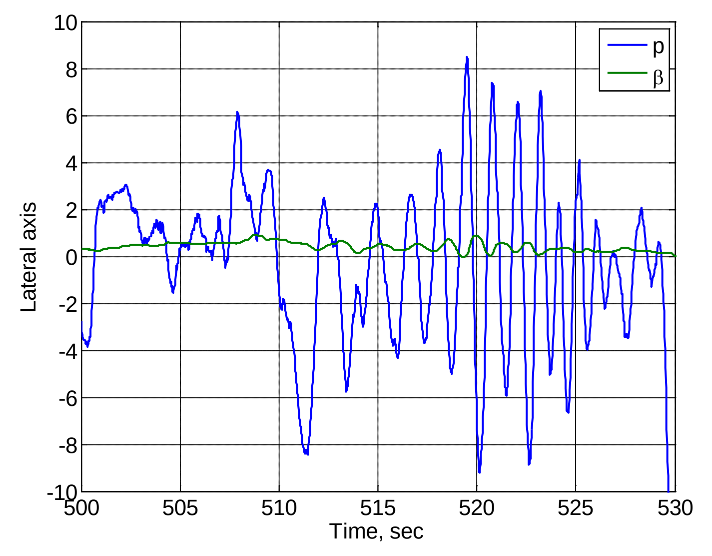
Unsteady Aerodynamic Modeling

- **Roll forced oscillations at $\alpha=12$:**
  - – Precise tracking of $\alpha=12$
    - – L1 longitudinal
  - – Allow free β response to roll wavetrain
    - Step doublet, Schroeder sweep, variable frequency Sinusoid

Schroeder Input

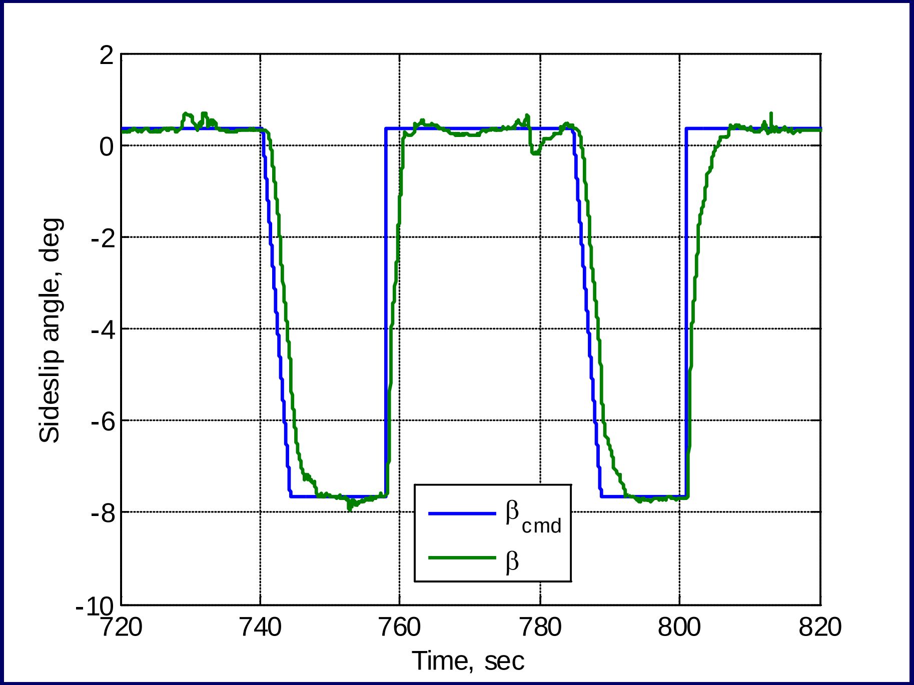


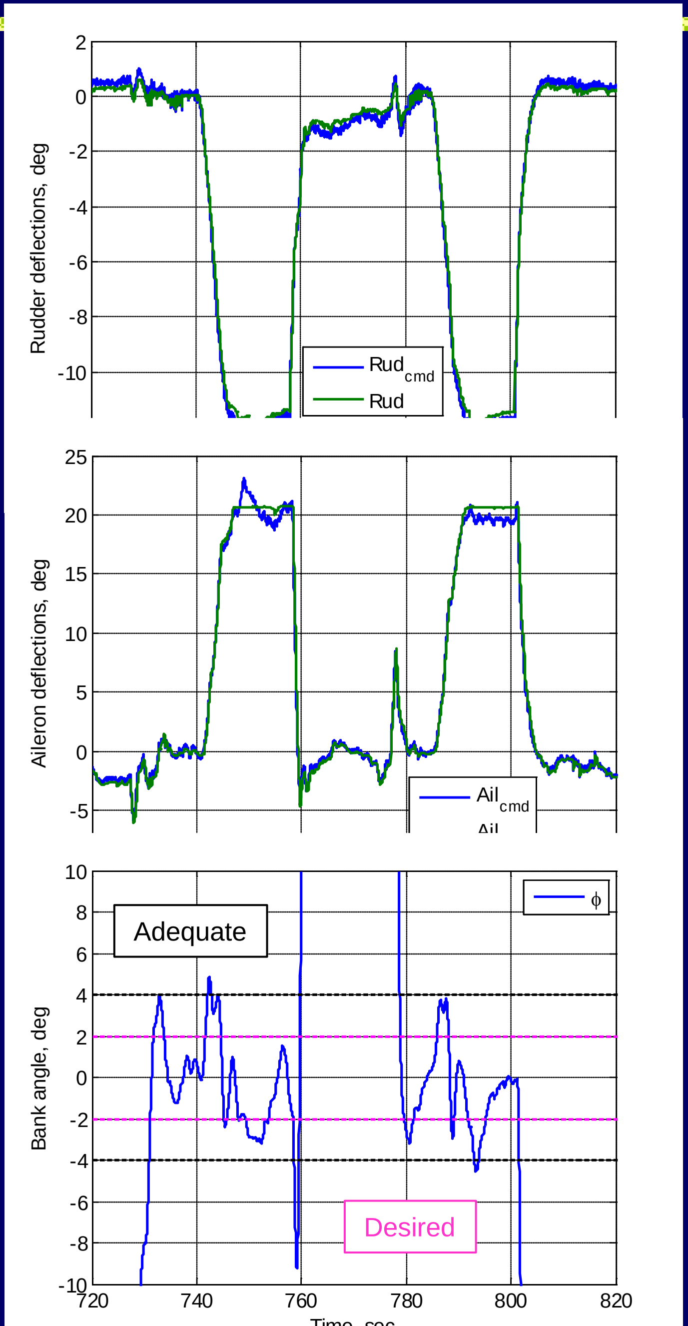




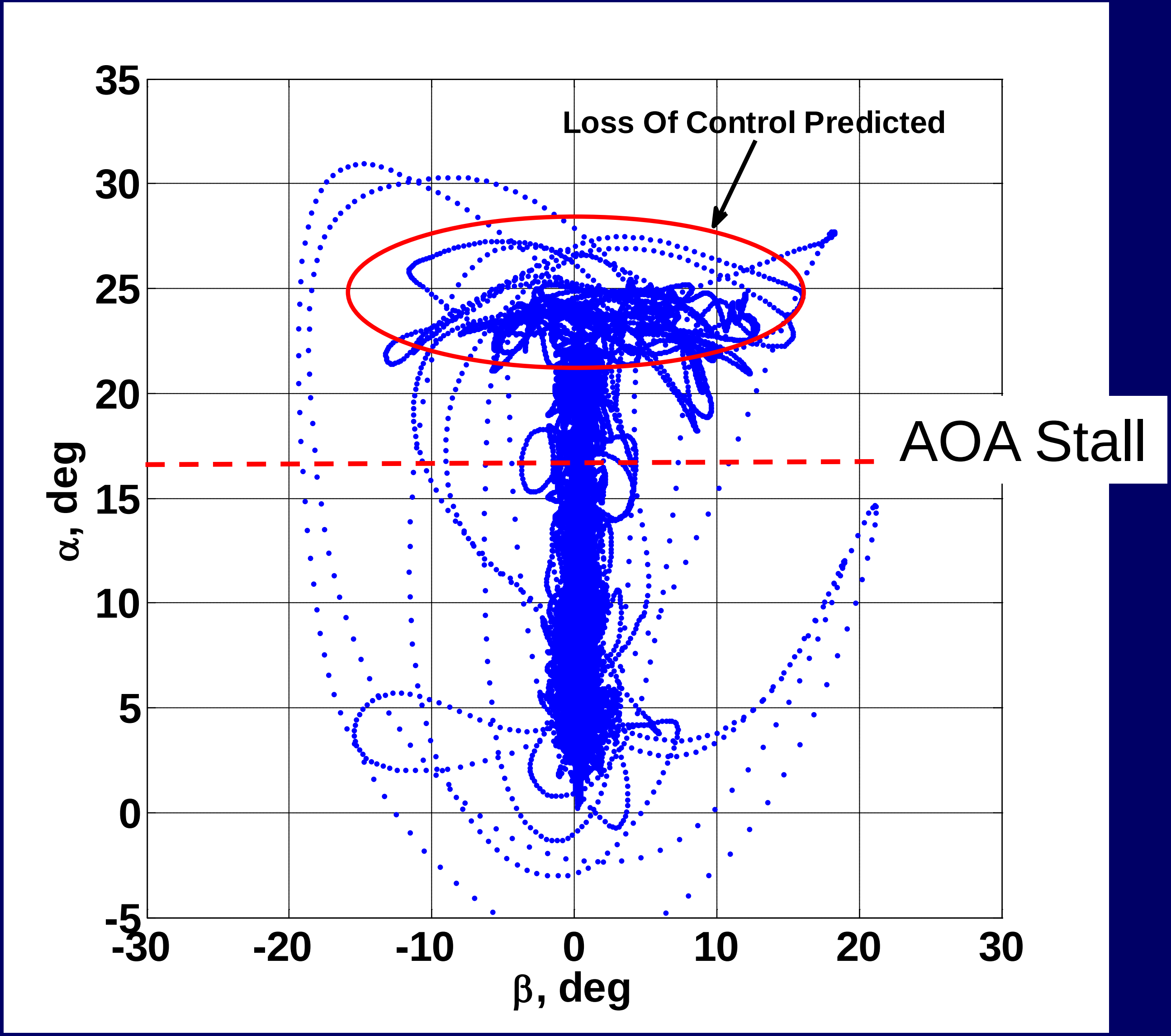
Sideslip Angle Vane Calibration (September 2010)

- Flat turn – hold target sideslip
  - Minimize lateral axis excursions



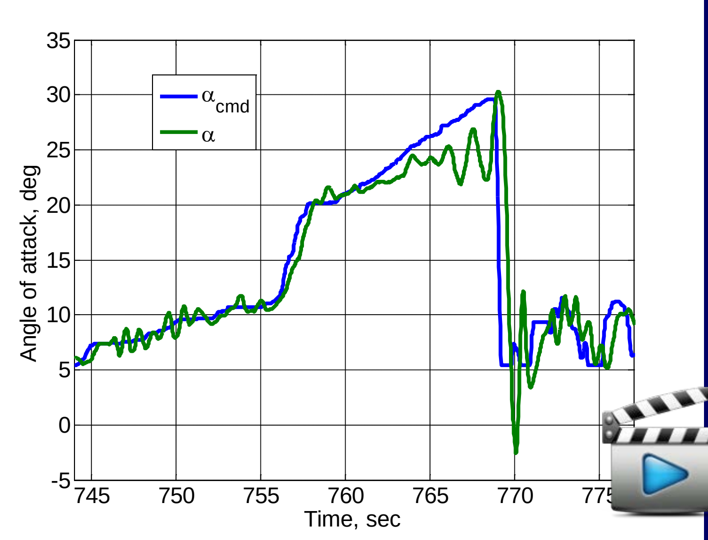


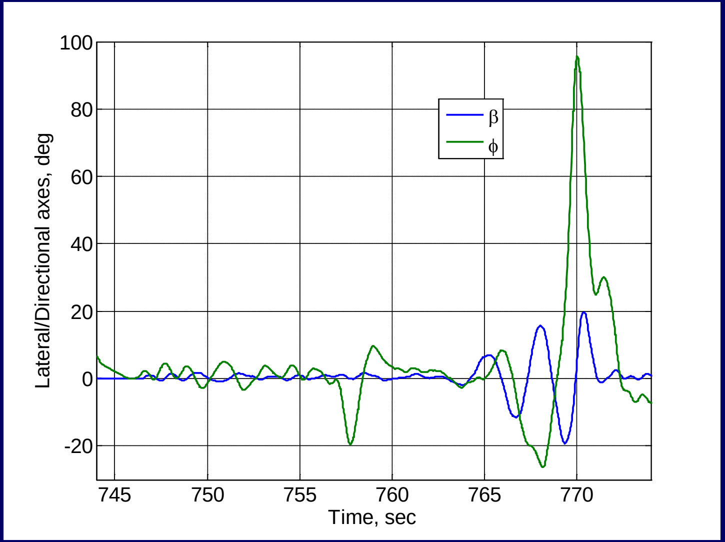
L_1 Supports Large Flight Envelope Modeling

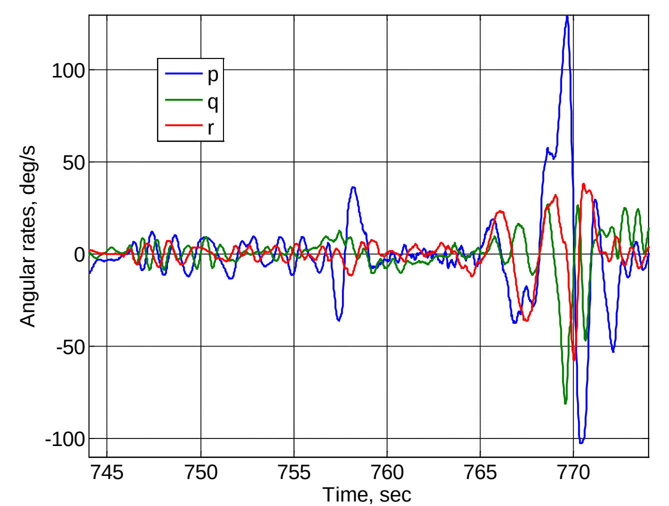


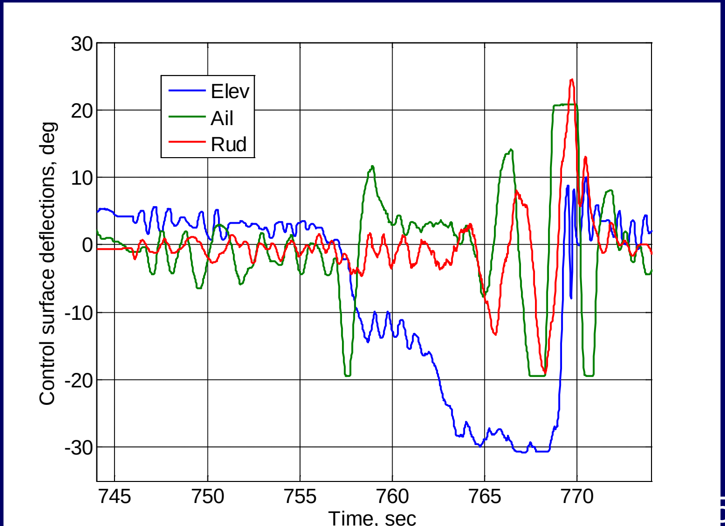
AOA Pull Through Stall and Departure

- **Flight 58 – active wavetrain through stall, departure and recovery, L1 adaptive control law in the feedback loop**
- **Reached departure conditions; aircraft <u>not fully controllable</u>**









Offset Landings (High Workload Tasks)

- **Initial offset:**
  - 90 ft. lateral, 1800 ft. downrange, 100 ft. above the runway
- **Performance boundaries:**
  - Desired: $|\phi| < 10$ deg; $|\gamma| < 1$ deg; landing box = 164’ x 12’
  - Adequate: $|\phi| < 20$ deg; $|\gamma| < 3$ deg; landing box = 363’ x 24’
- Flying qualities ratings taken for **nominal, neutrally stable, unstable airplane**

	S2S	L1 AFCS
Nominal	*CHR*4 (HQ L2)	*CHR*3 (HQ L1)
Neutral Stability	*CHR*10 (uncontrollable)	*CHR*5 (HQ L2)
Unstable	--	*CHR*7 (HQ L3)


CHR 3

Nominal


CHR 5

Neutrally Stable


CHR 7

Unstable

GTM T2 :: Summary of Flight Test Evaluation (NASA)

- **All-adaptive FCS** that takes care of large changes in aircraft dynamics
  - ✓ **No baseline to assist**

- A **single controller design** at a nominal flight condition (80KEAS, 4 deg AOA) to provide satisfactory FQ and robustness for the **entire large envelope,** flown to the corners of flight envelope, **$\alpha \approx 28+$ deg, $\beta = |8|$** **(this was the ONLY controller cleared for High AoA flight)**
  - ✓ **No gain scheduling of control parameters**

- **Predictable response** to the pilot under stability degradation and ***graceful performance degradation*** once nominal response was unachievable

- **Departure resistant in post-stall flight:** L1 provides a **controllable aircraft** to the pilot and facilitates **safe** return to normal flight

- Aerodynamic modeling in highly nonlinear regimes and real-time dynamic modeling of the **departure-prone edges** of the flight envelope
  - ✓ **Modeling of unsteady aerodynamics at stall**

- The **post-stall aerodynamic test envelope** was expanded to **28° angle of attack**

- L_1 controller enabled operation **near stall and departure for longer periods of time**, which allowed collection of data for a wide range of flight conditions, **including low angle of attack, moderate angle of attack, stall, departure and recovery,** with **a single maneuver.**

What’s next at NASA: iReCoVeR


GTM (5.5%)


GMAT (15%)

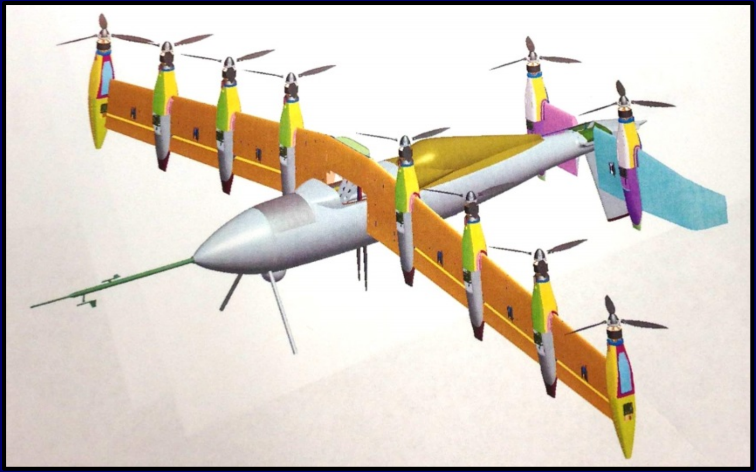

TCM

- **Autonomy:**
  - ✓ *Autonomous taxiing, take-off, up-and-away flight, and landing;*
  - ✓ *Pilot-in-the-loop FCLs for research tasks.*

NASA: Unconventional Aircraft Configurations

- *55lb Greased Lightning VTOL UAV*

-- ≈6 ft in length and ≈10 ft in wingspan
-- 10 motors, 9 surfaces, 2 tilt mechanisms
-- 3 phases of flight
•*Hover*
•*Transition*
•*Forward flight*



GL10

- *Commercial off-the-shelf UAV*
  - ✓*~103lb weight*, ~12.5 ft wingspan
  - ✓Single rear-facing propeller
  - ✓6 control surfaces
    - ✓2 Ailerons
    - ✓2 Flaps
    - ✓2 Ruddervators

BAT4

Other Craft in Europe

DA-42 (TUM)

Generic helicopter model

Hexarotor (UMD)

Gripen-like fighter (SAAB)

Cessna Citation II (TUD)

Generic Missile Model

Quad (TUM)

Quad (viacopter)

L_1 in Other Application Domains

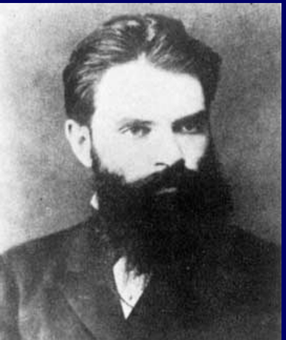
- L_1 control of hard disk drives (Seagate, USA)
- L_1 control of boats (Raymarine, UK)
- L_1 control of pumps (Caterpillar, USA)
- L_1 control of drilling pressure (StatOil, Norway)
- L_1 control of rotary steerable system (Schlumberger, England)
- L_1 control of fiberoptics (Cedric Langbort, UIUC)
- L_1 control of biological networks (Vishwesh Kulkarni, UMN)
- L_1 control of anesthesia (Carolyn Beck, UIUC)
- L_1 control of bioassistive devices (Harry Dankowicz, UIUC, jointly with CU Aerospace)
- L_1 control of smart materials with hysterisis (Ralph Smith, NCSU)
- L_1 control of nuclear power plants (Asok Ray, PenState)
- L_1 control for iterative learning framework (Kira Barton, UMich)
- L_1 control for time-critical ISR missions (Isaac Kaminer, NPS)
- L_1 control of DA-42 aircraft (TU of Munich, Germany)
- L_1 control of Cessna aircraft in SIMONA (TU of Delft, The Netherlands)
- L_1 control of engines (Chengyu Cao, UConn, P&W, UTRC)
- L_1 control of micro UAVs (Randy Beard, BYU)
- L_1 control of rotorcraft (Jon How, MIT)

Conclusions

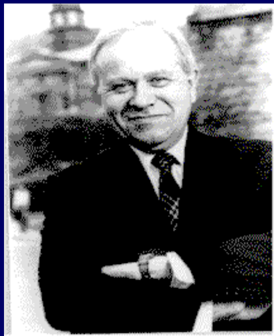
- What do we need to know?
  - Boundaries of uncertainties → sets the filter bandwidth
  - CPU (hardware) → sets the adaptive gain

Performance limitations reduced to hardware limitations

- Decoupling of estimation from control
  - estimation loop ***free*** of uncertainties
  - performance can be predicted ***a priori***
  - robustness/stability margins can be quantified **analytically**
  - **performance scales similar to linear systems**
- Theoretically justified **Verification & Validation tools** for feedback systems → at reduced costs



with very short proofs!



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- ☐ Steven Pelech (MS. Student ME)
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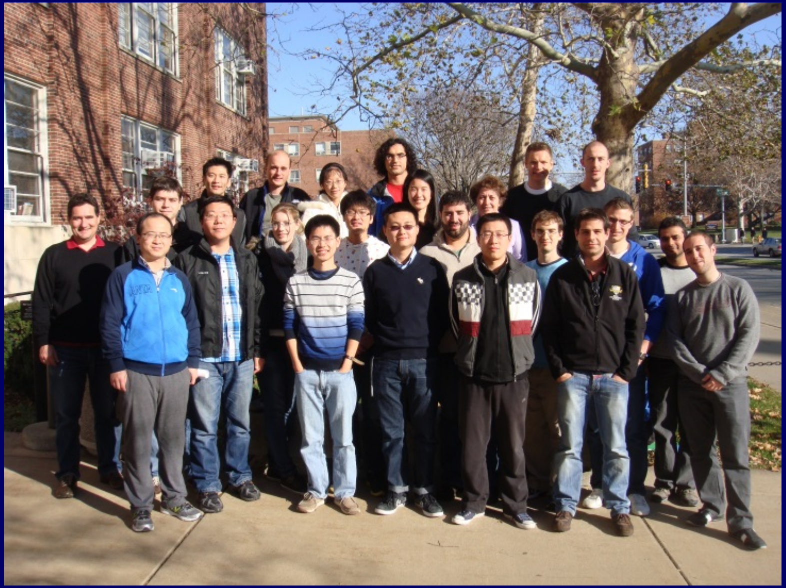

Collaborations:

- ☐ **Chengyu Cao (University of Connecticut)**
- ☐ **Isaac Kaminer (NPS)**
- ☐ **Irene Gregory (NASA LaRC)**

Sponsors: AFOSR, AFRL, ARO, ONR, Boeing, Raytheon, NASA, NSF

More information can be found…

http://naira.mechse.illinois.edu

http://www.unmanned-dynamics.com/

http://www.youtube.com/user/nhovakimgroup

"In theory there is no difference between theory and practice. In practice there is." – Yogi Berra (1925)