# $L_1$ Adaptive Control and Its Transition to Practice


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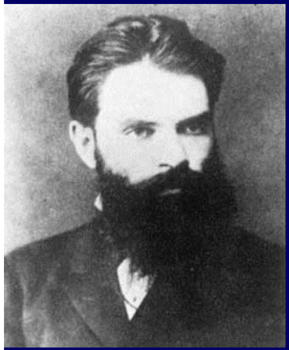
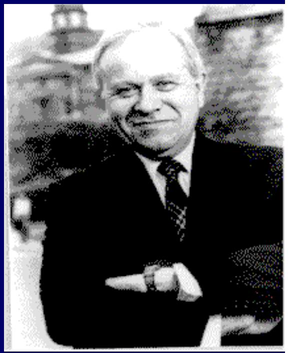


**A. M. Lyapunov**
**1857-1918**



**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**

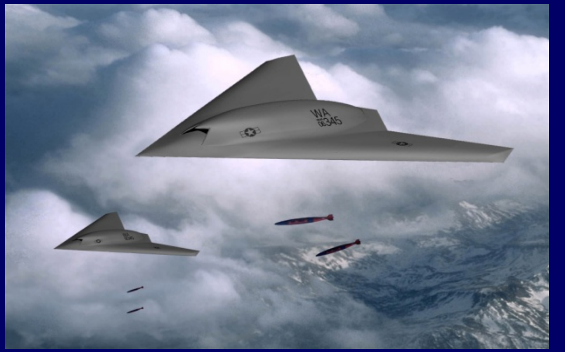
**Crash site of X-15A-3**

# 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

# Control Design Methods

## ❖ Non-model Based Approach

- PID Control
  - Tuning of 3 gains to achieve desired specifications
- Unfalsified Control (Safonov 1996)
  - Data driven online selection of a controller among a predefined set of candidates
- Fuzzy Logic Control (Zadeh 1965)
  - Smooth switching of control strategy based on predefined events or rules (based on fuzzy logic)
- Black Box Adaptive Control
  - Relies mostly on aposteriori information. Attempts to identify the behavior of the system online.
- ...

## ❖ Model Based Approach

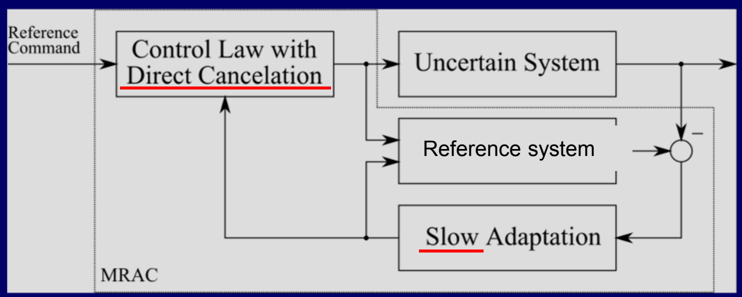
- LQR Control
  - For a given system model generate control which minimizes a quadratic cost function
- Nonlinear Dynamic Inversion
  - A method to cancel a known system nonlinearity.
- Internal Model Principle (IMP) (Francis 1976)
  - Controller must incorporate known model of disturbance in order to compensate for it
- Internal Model Control (IMC) (Morari 1982)
  - Controller incorporates nominal model of the system
- $H_\infty$ methods (Zames, Doyle, Tannenbaum 1970's)
  - Robust control design for an uncertain system is represented as an optimization problem
- Gray Box Adaptive Control
  - Structure of the system and apriori parameter knowledge is available
- Model Predictive Control
  - Optimal control action generated based on constraints

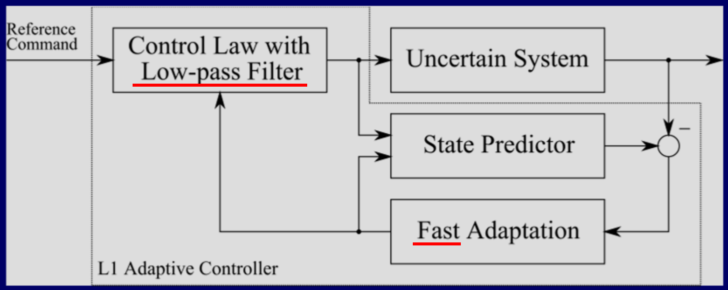
**Design procedure of model based approach relies on the apriori available model of the system**

# Adaptive Control Solutions

❖ **Model Reference Adaptive Control** ❖ **$L_1$ Adaptive Control**

## << Similarity in Structure >>



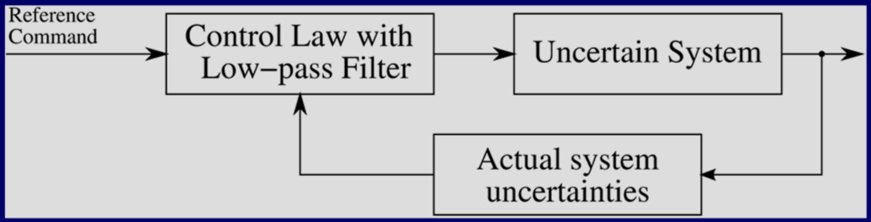

## << Departure in Philosophy >>

- The **current estimated** values are used to compensate for the uncertainty
  - Estimation and control run in the same frequency range
  - Resulting **coupling may lead to poor performance** and instability
- Performance of the estimation loop depends on the adaptation rate
  - Higher rates affect robustness and transient
  - Tradeoff is resolved by adaptation rate
- ***MRAC aims for complete compensation of the uncertainty***
  - **Ambitious (not achievable) control objective**

- The control signal is generated using a **lowpass filter**
- Large adaptation rates shift estimation dynamics to high frequency range
  - **Estimation and control are decoupled**
  - Robustness is not affected by adaptation rates
- Performance of the estimation loop can be arbitrarily improved by increasing the adaptation rates
- ***$L_1$ adaptive control system aims for partial compensation of the system uncertainty within the bandwidth of the lowpass filter***
  - **Achievable control objective**

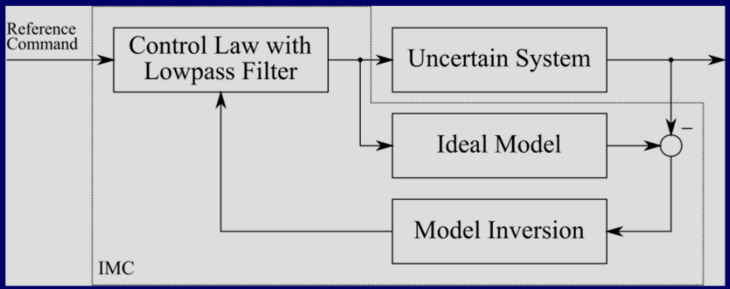
# $L_1$ Adaptive Control and IMC Architectures

- $L_1$ adaptive controller **shares the philosophy with Internal Model Controller**
  - Both architectures aim for compensation of the system uncertainty within the **bandwidth of the lowpass filter**





- $L_1$ adaptive controller uses **fast estimation loop** to obtain the estimate of the system uncertainty
- IMC controller **inverts the ideal system dynamics** to measure the uncertainty at the system input

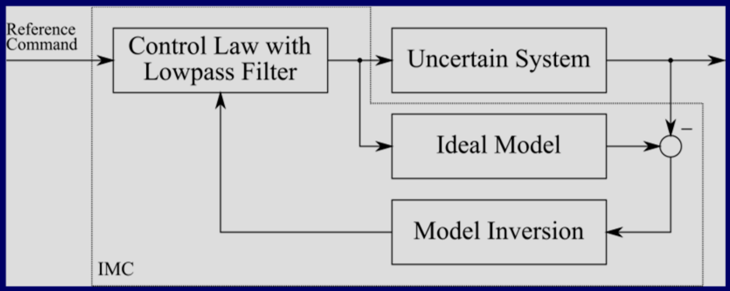




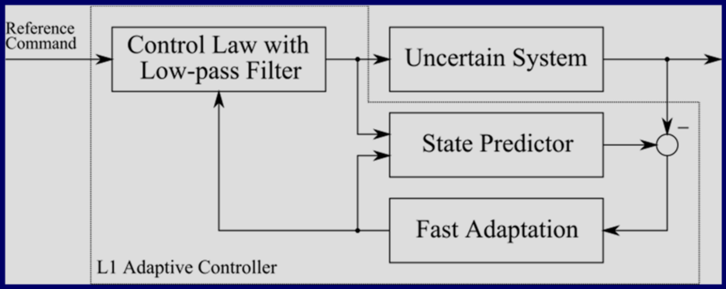
- $L_1$ adaptive controller achieves the input-output behavior of IMC controller in the presence of fast adaptation rates
  - We refer to IMC controller as **"limiting controller"**
  - From input-output behavior perspective we can talk about equivalence of these control methods
  - **Are there any differences between $L_1$ and IMC from other points of view?**

# Comparison of the Robust Architectures

**Internal Model Control**



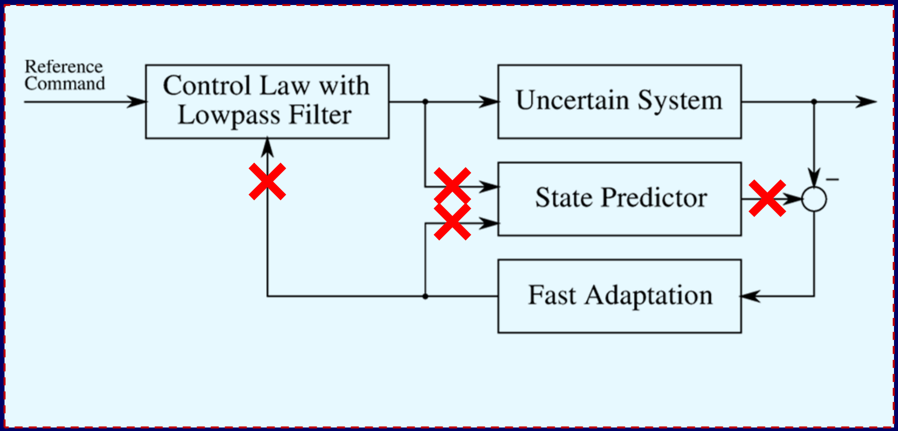

**$L_1$ Adaptive Control**



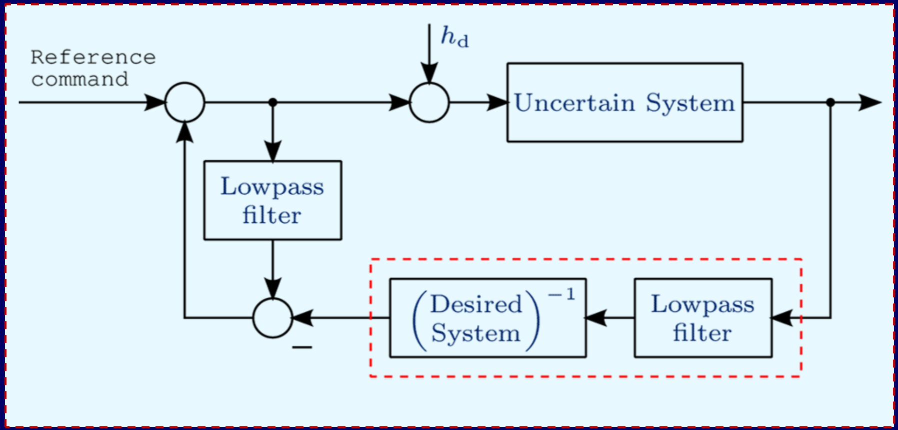

- ❖ IMC requires explicit inversion of the ideal model!
  - Computation of the system inverse may become a limitation!
- ❖ **The estimation loop of $L_1$ adaptive controller does not require the knowledge of the system inverse**
  - It computes the approximate system inverse through fast estimation
  - Beneficial from **implementation perspective**
- ❖ $L_1$ adaptive controller offers significantly richer control architecture
  - Straight forward modification of the estimation loop to address real world requirements without affecting the control law performance

# $L_1$ Adaptive Controller and Disturbance Observer

## $L_1$ adaptive controller



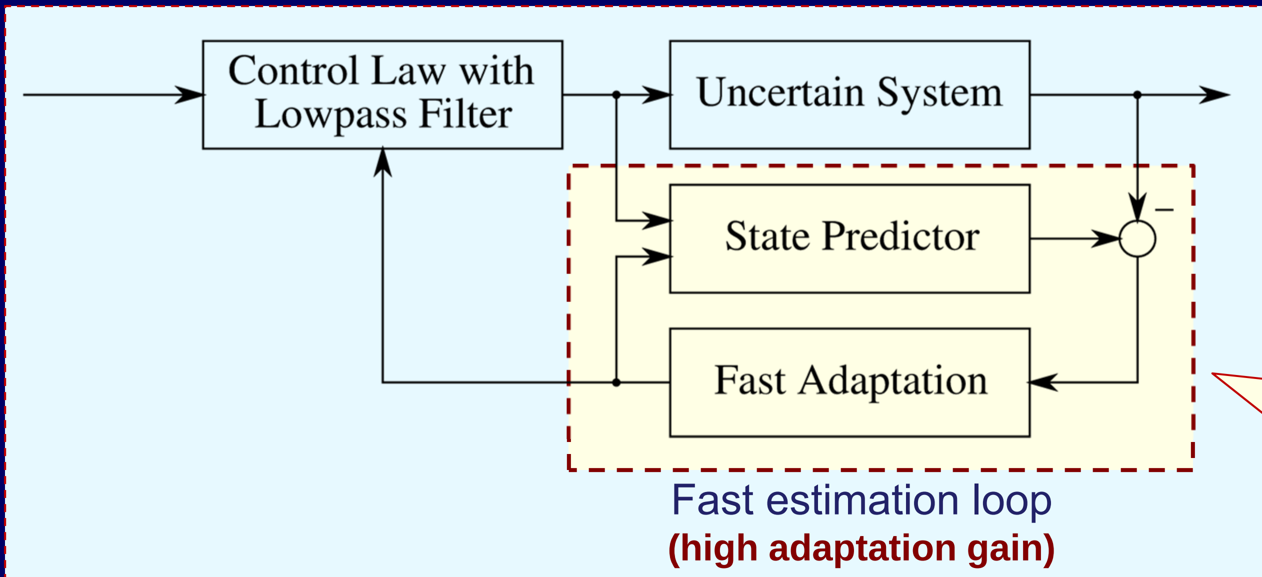

## Disturbance observer




❌ - suitable modification point

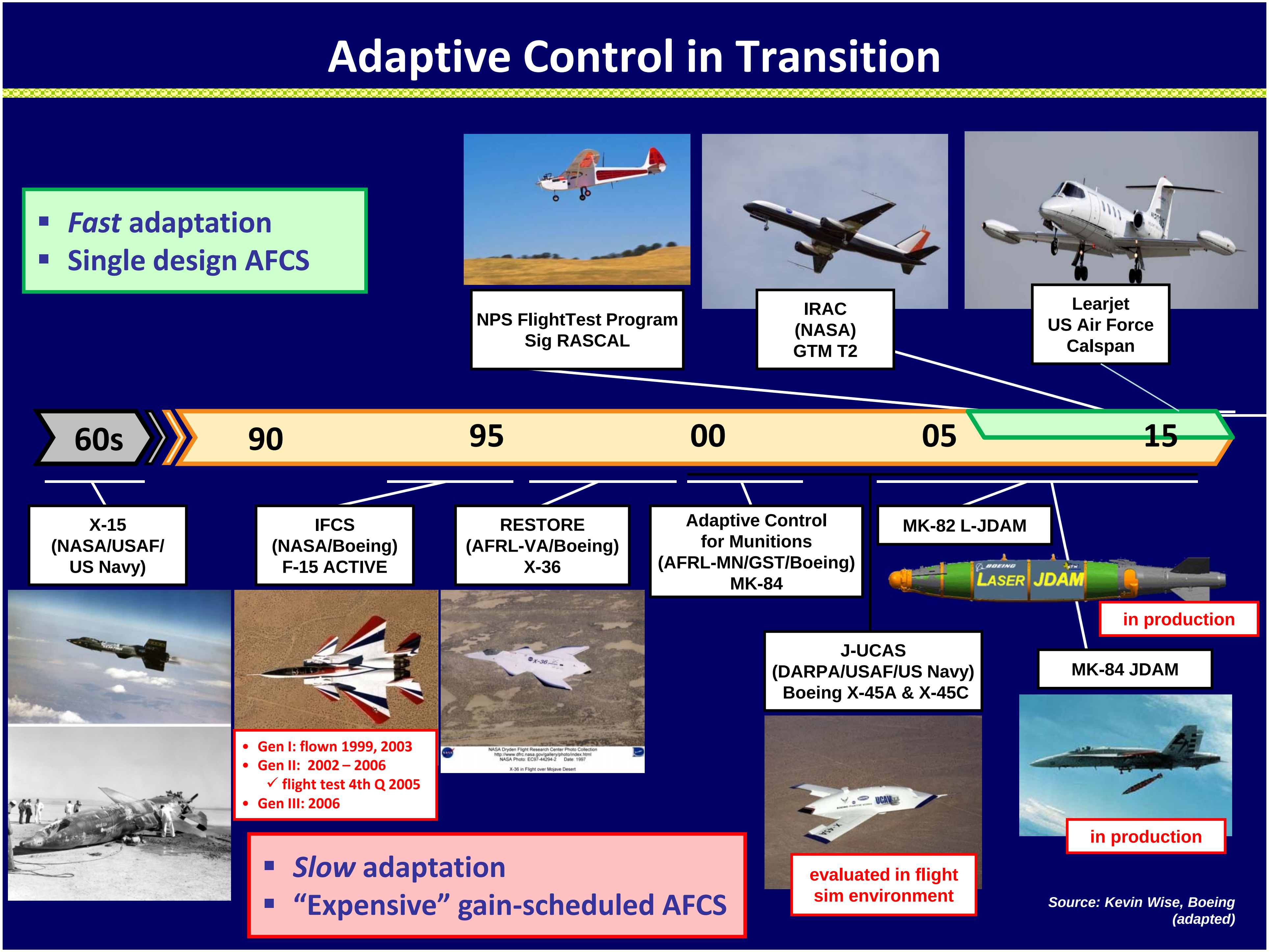
- **Estimation loop of $L_1$ adaptive controller can be modified to incorporate known system nonlinearities,** which helps to improve the closed-loop system performance
- Non-adaptive controller **does not offer** such intuitive modifications
- Instead, for the non-adaptive controller **one needs to compute the system inverse** with account of all **nonlinearities, including hardware constraints**, etc.

# $L_1$ Adaptive Architecture: Decoupling Estimation from Control




Implemented inside CPU
**No possible uncertainty**
in the loop

- $L_1$ adaptive controller **achieves decoupling of estimation from control,** which **eliminates uncertainties from the estimation loop**
- **Decoupling** of **estimation** from **control** allows for various modifications of the estimation scheme **without violating robustness** of the system
- MRAC **does not have decoupling** between control and estimation
- Non-adaptive controller **does not have an estimation loop**



Adaptive Control in Transition
Fast adaptation
Single design AFCS
NPS FlightTest Program
Sig RASCAL
IRAC
(NASA)
GTM T2
Learjet
US Air Force
Calspan
60s
90
95
00
05
15
X-15
(NASA/USAF/
US Navy)
IFCS
(NASA/Boeing)
F-15 ACTIVE
RESTORE
(AFRL-VA/Boeing)
X-36
Adaptive Control
for Munitions
(AFRL-MN/GST/Boeing)
MK-84
MK-82 L-JDAM
LASER JDAM
in production
Gen I: flown 1999, 2003
Gen II: 2002 – 2006
✓ flight test 4th Q 2005
Gen III: 2006
J-UCAS
(DARPA/USAF/US Navy)
Boeing X-45A & X-45C
MK-84 JDAM
in production
Slow adaptation
“Expensive” gain-scheduled AFCS
evaluated in flight
sim environment
Source: Kevin Wise, Boeing
(adapted)

# 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

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

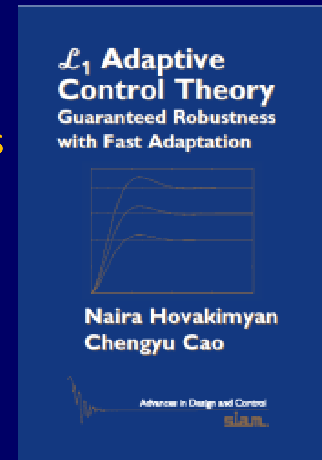
Moreover, there exists $\Gamma_0$ , such that if $\Gamma>\Gamma_0$ , the time-delay margin is guaranteed to stay bounded away from zero

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

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.

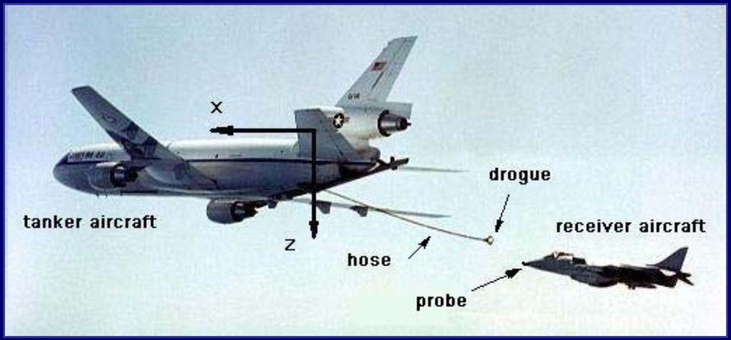
# Basics of the Theory

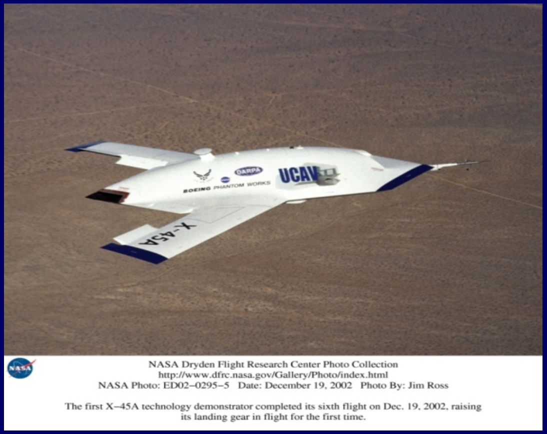



- **State-Feedback:**
  - $L_1$ Adaptive Control for Systems with TV Parametric Uncertainty and TV Disturbances
  - $L_1$ Adaptive Control for Systems with Unknown System Input Gain
  - $L_1$ Adaptive Control for a class of Systems with Unknown Nonlinearities
  - $L_1$ Adaptive Control for Nonlinear 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







# Integrated Resilient Aircraft Control (IRAC)

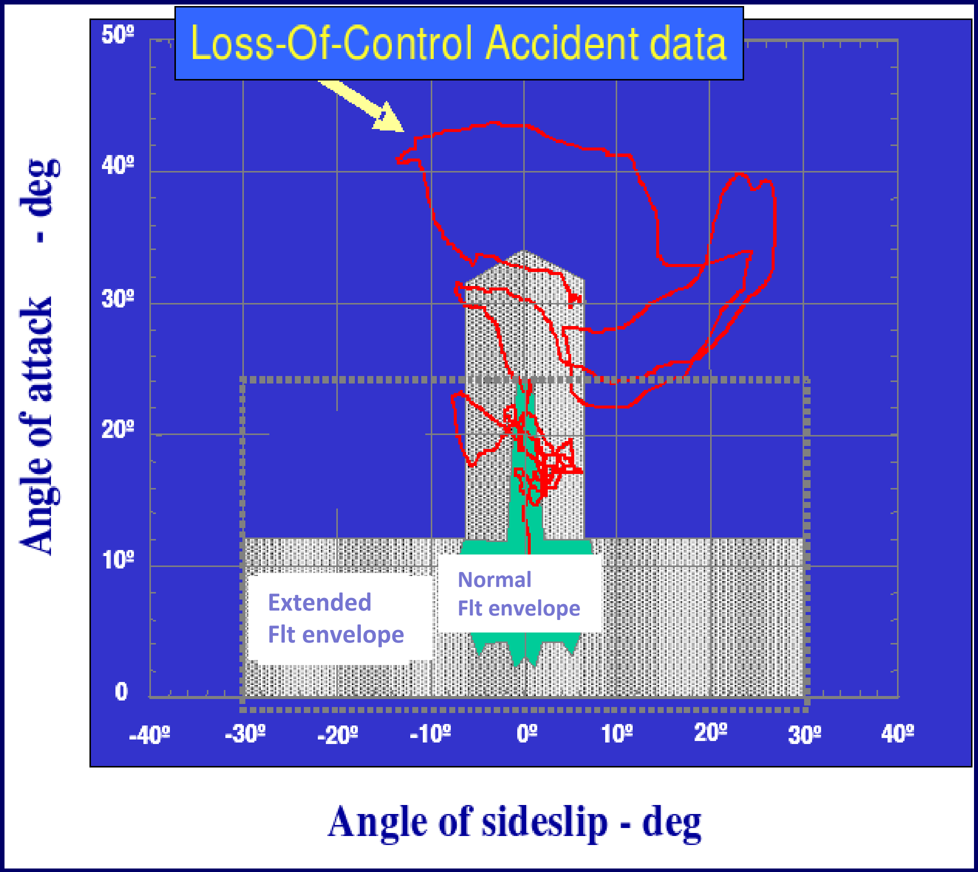
*IRAC research is focused on loss-of-control, failure and damage scenarios, and their mitigation though the application of adaptive control.*

***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**:

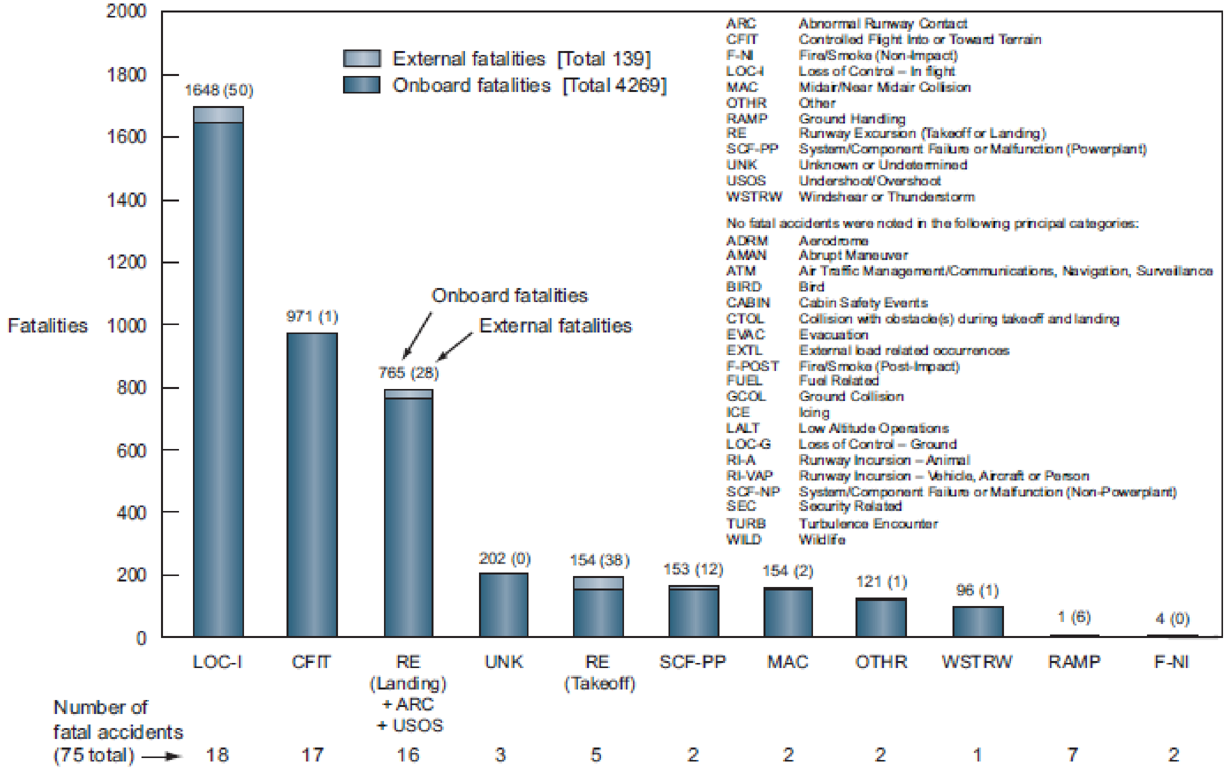
- ➢ Need for **transient performance guarantees**
  - ➢ **Predictable response**
- ➢ Need for **fast adaptation**



# Aircraft Loss of Control

## Fatalities by CAST/ICAO Common Taxonomy Team (CICTT) Aviation Occurrence Categories

### Fatal Accidents – Worldwide Commercial Jet Fleet – 2003 Through 2012




*Note: Principal categories as assigned by CAST.*

*For a complete description of CICTT Aviation Occurrence Categories, go to: http://www.intlaviationstandards.org/*

# 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 #: | Target KIAS | Maneuver: | Target Altitude |
|---|---|---|---|
| **01** | **$V_{ref}$+5** [redacted] | **BASELINE Param. Est.** | [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 #: | Target KIAS | Maneuver: | Target Altitude |
|---|---|---|---|
| **02** | **$V_{ref}$+5** [redacted] | **FCL BUILDUP** | [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**

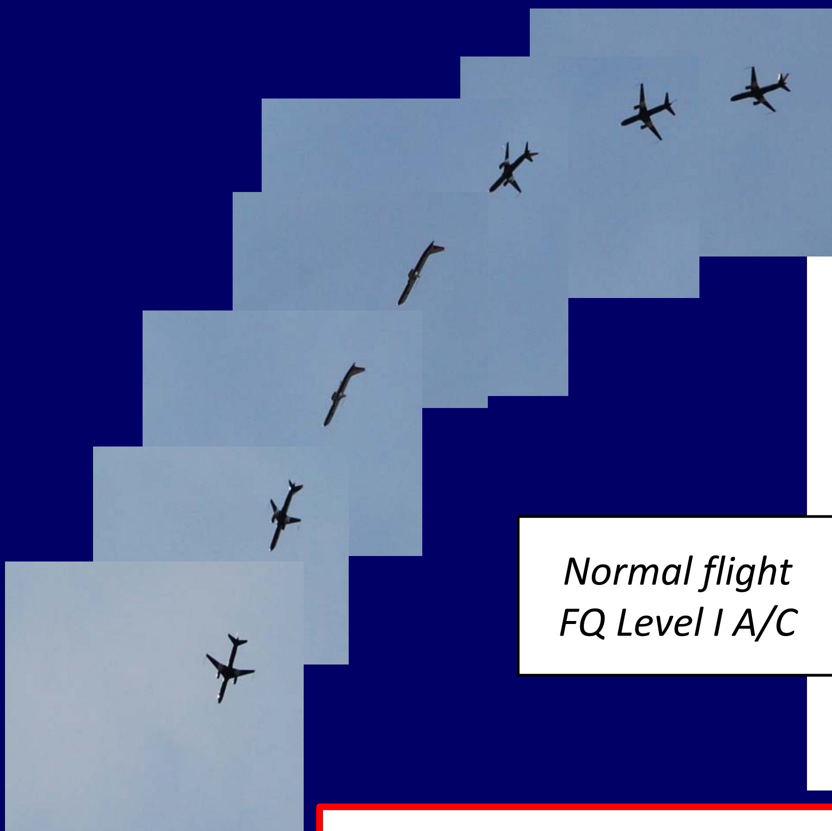
**KIO: ALT>** [redacted]
**KIO: ALT<** [redacted]

**TAKE IT:**
**ALT <** [redacted]

# GTM T2 :: Flight Test Evaluation (June 2010)

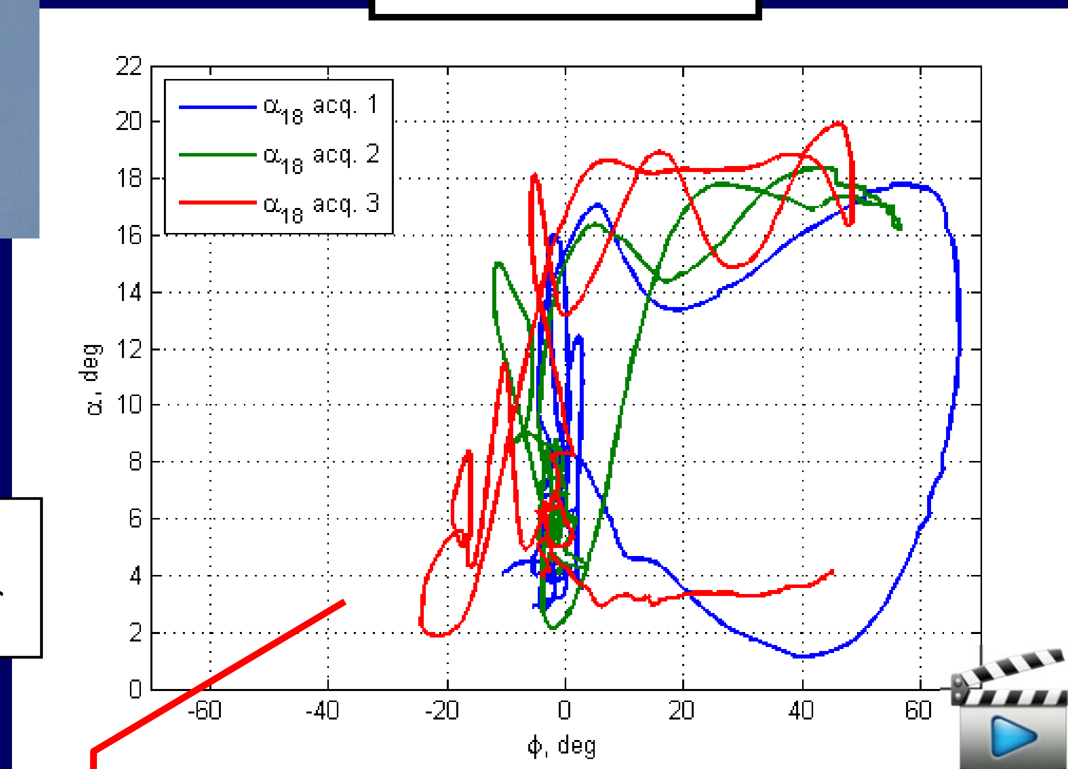
## Post-stall, high angle of attack flight

- **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*

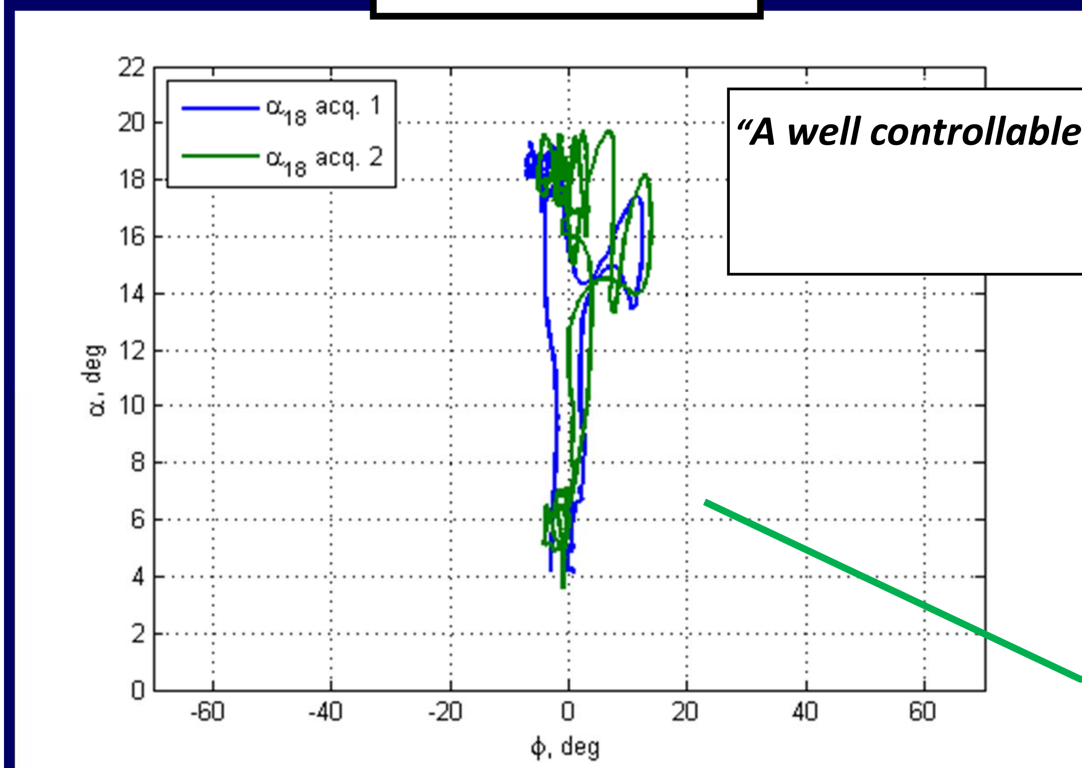
~12.5 mins of flight with L1

# 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***

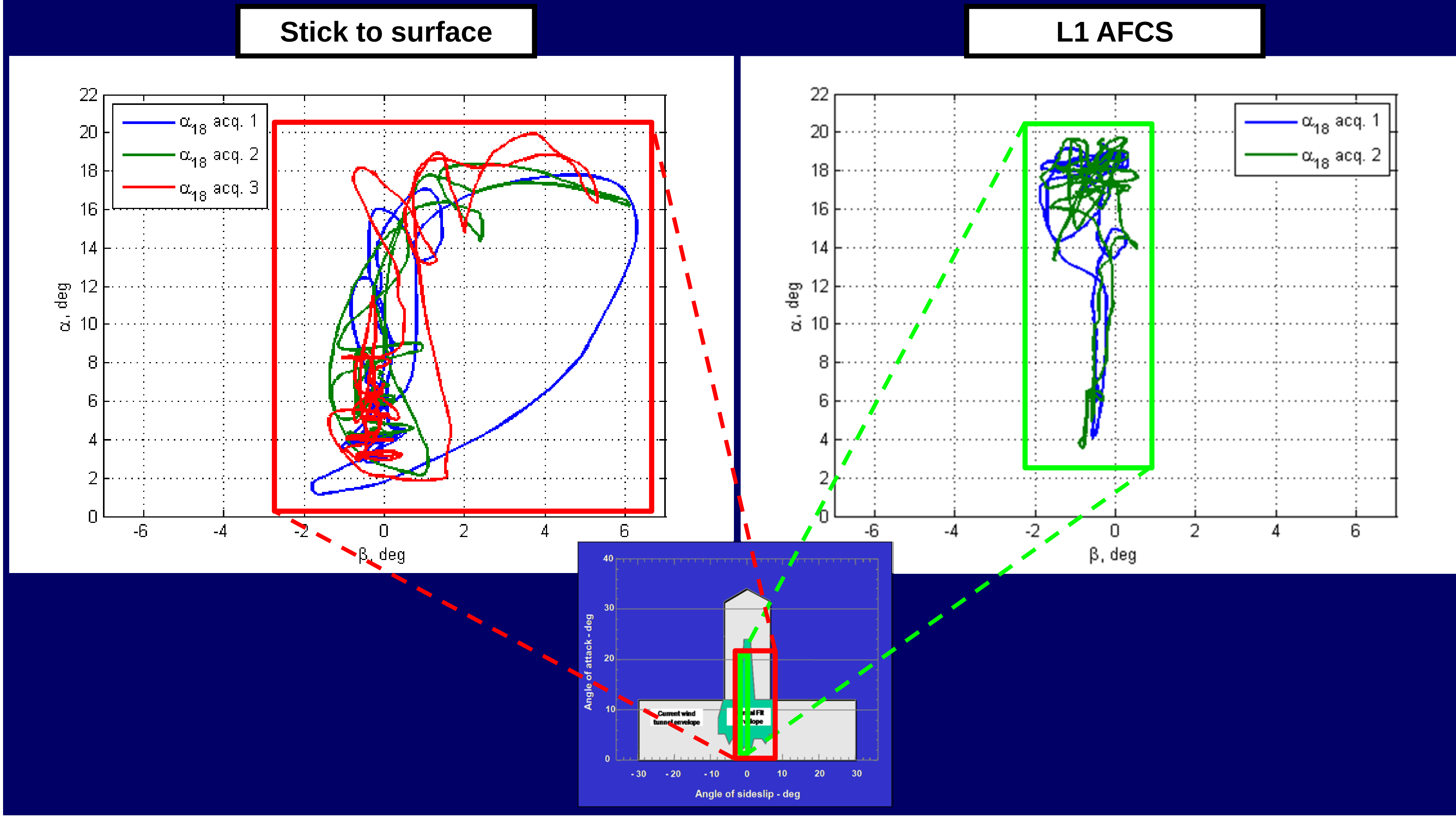
*Two AOA=18deg acquisitions*

*with L1 AFCS*

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

## Post-stall, high angle of attack flight

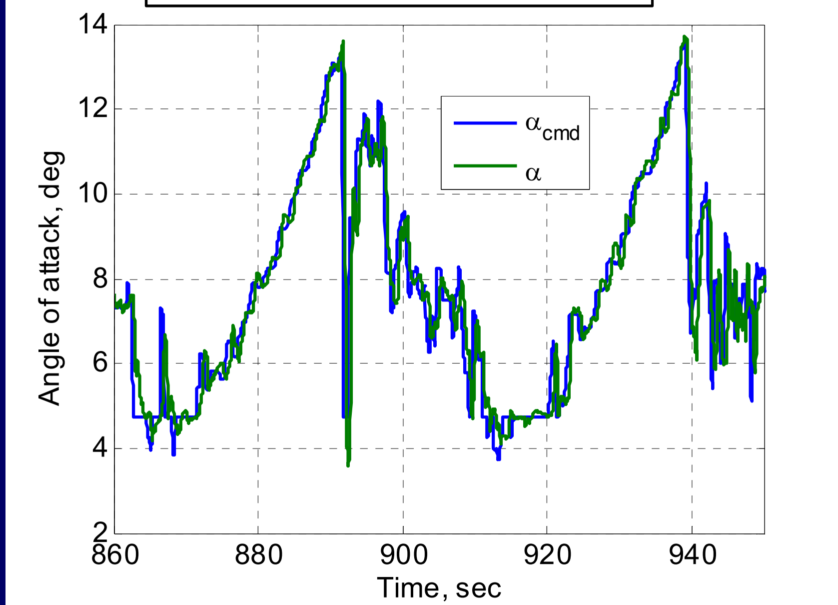
- **L1 provides departure resilient control for aircraft in post-stall flight**

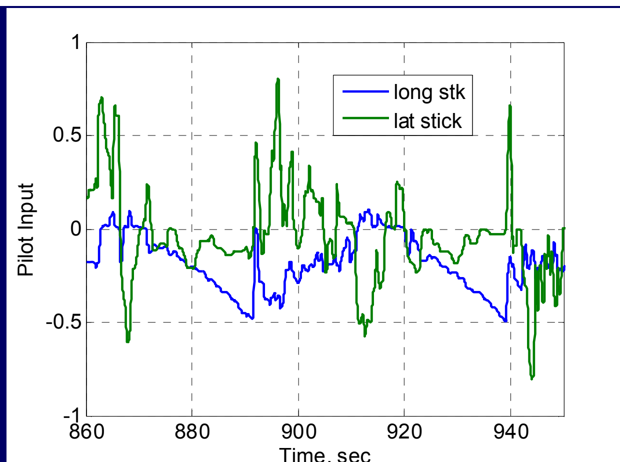


# GTM T2 :: Flight Test Evaluation (September 2010)

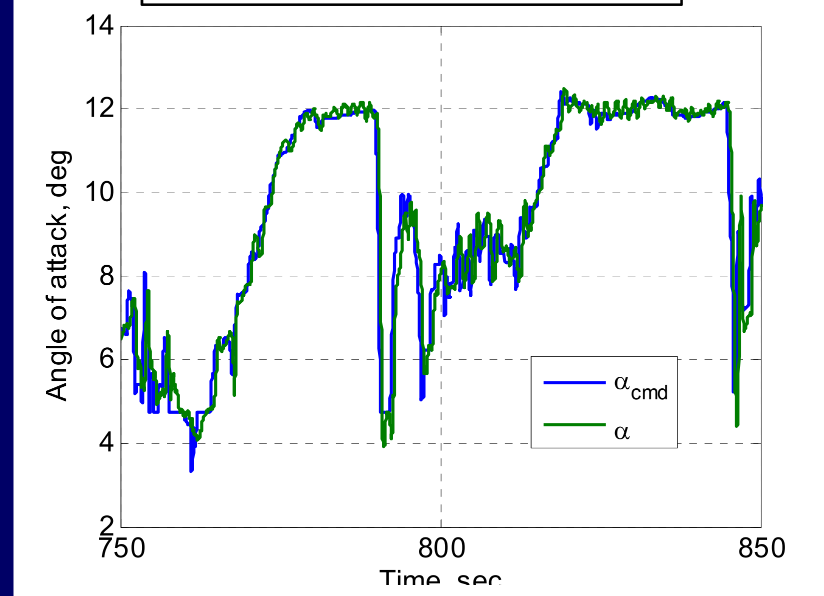
## Angle of Attack Vane Calibration: Stall occurs between 12 and 13 degrees

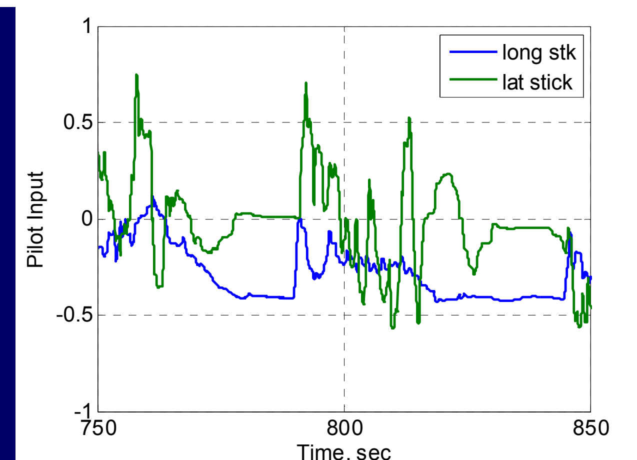
Variable AoA Strategy




Constant AoA Strategy

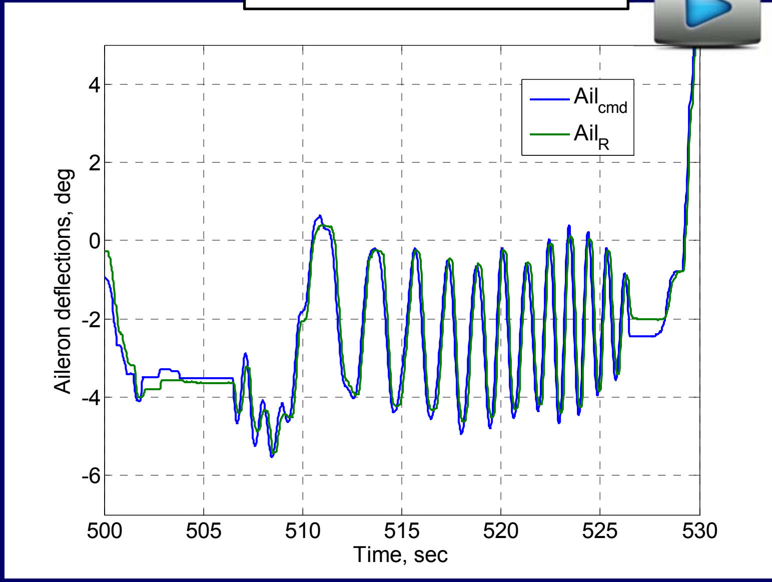


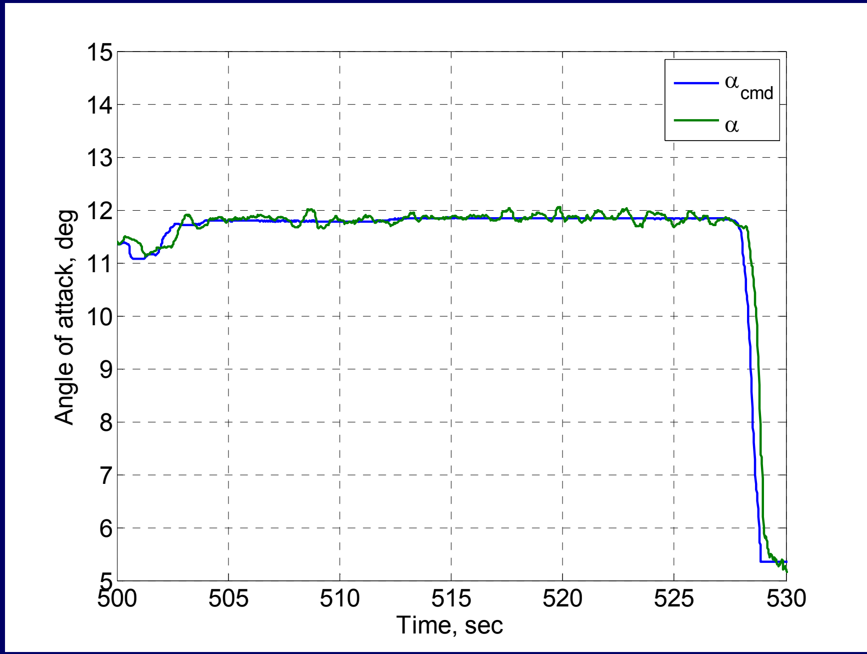



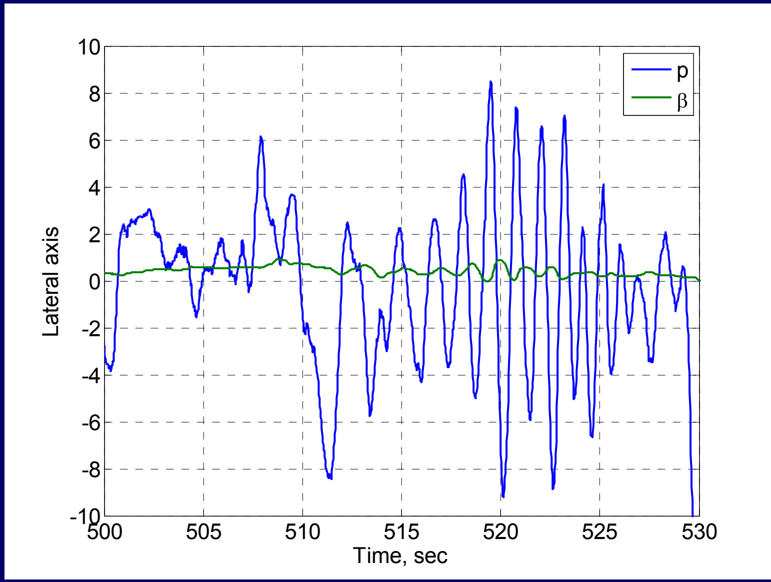
# Unsteady Aerodynamic Modeling

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

Schroeder Input

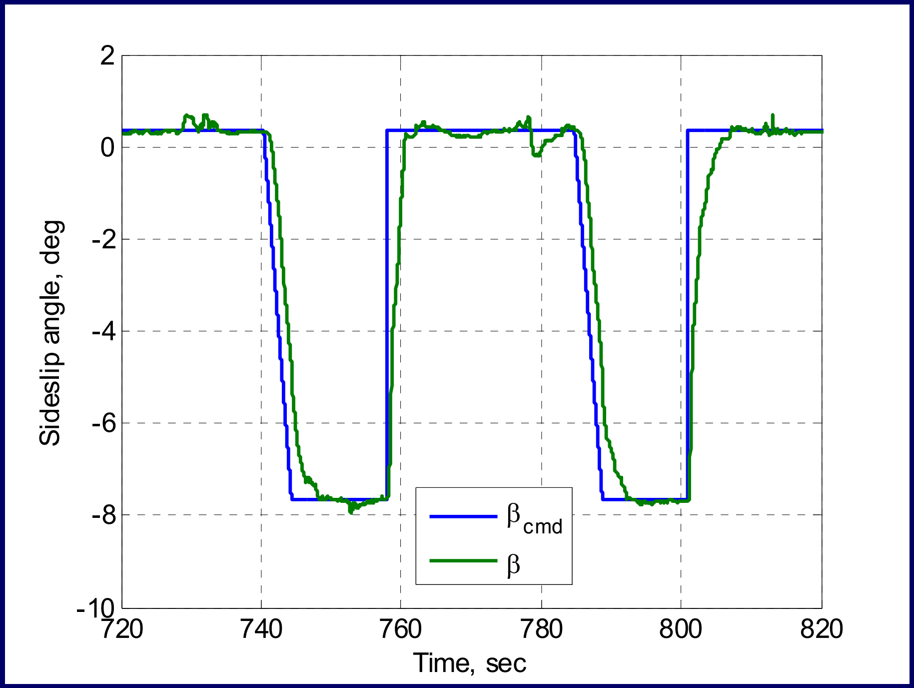


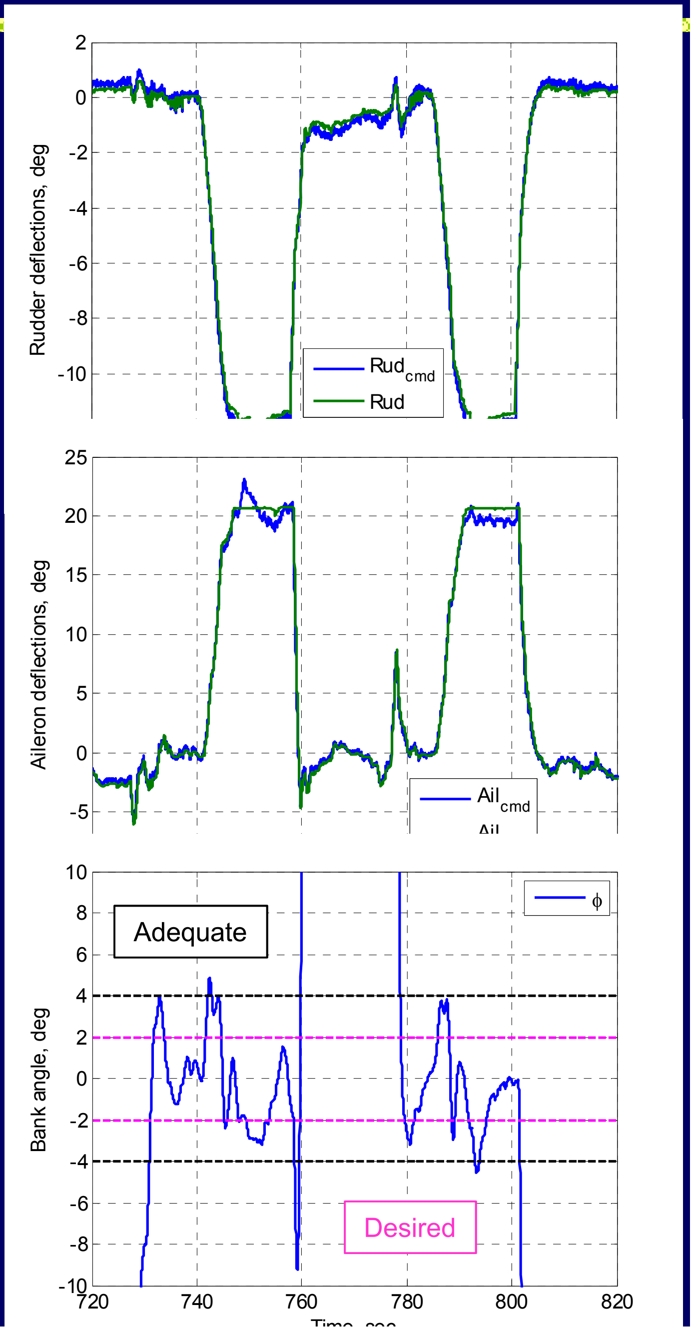



# Sideslip Angle Vane Calibration (September 2010)

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

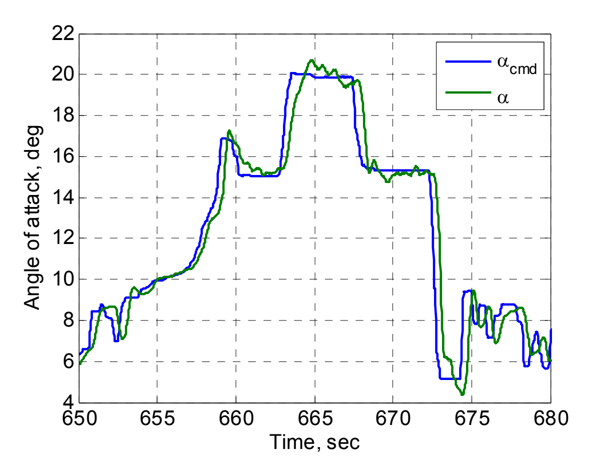


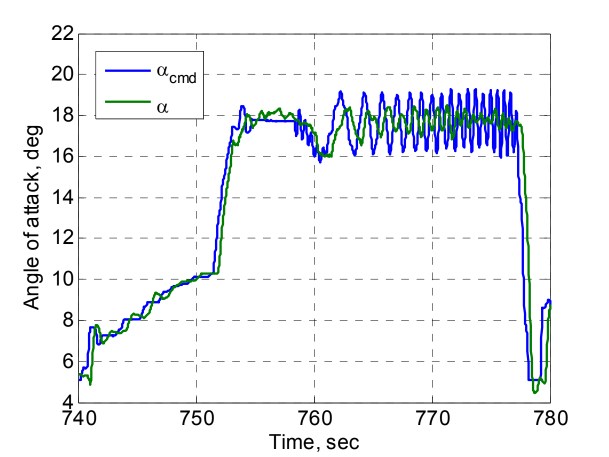
# Unsteady Aero :: High AOA Tracking (September 2010)

- Modeling **unsteady aerodynamics** by emulating the dynamic motion in the wind tunnel – determining efficacy of GTM to be a **<u>“flying wind tunnel”</u>**
- Target AOA = 18 deg – post-stall
- Injected inputs for L1 FCL to track – Step, Schroeder, Sinusoids

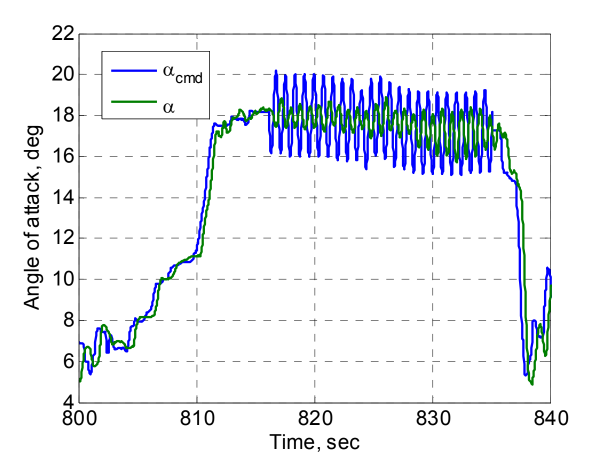
**Step Input**




**Schroeder Input**

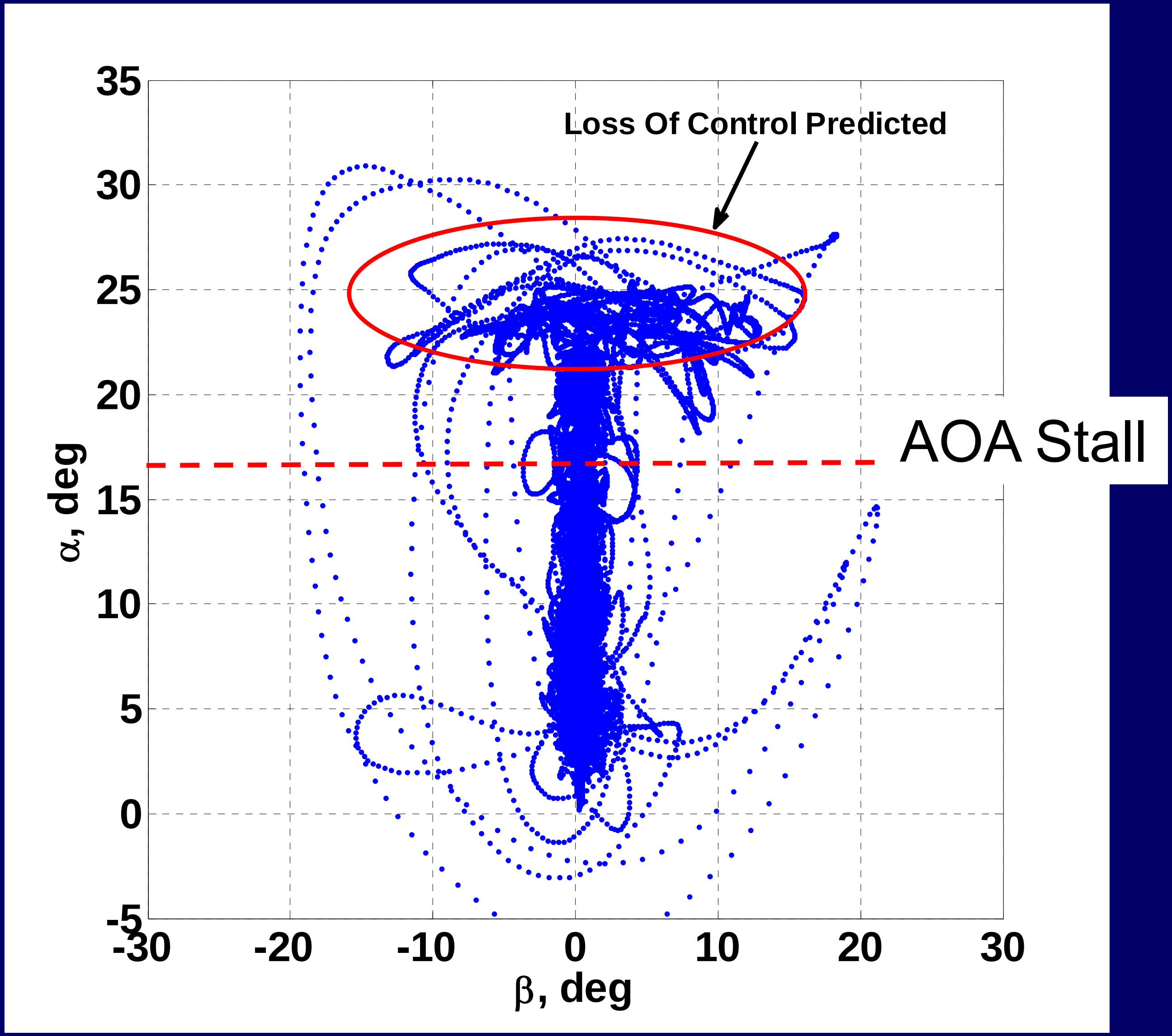



**Sinusoids Input**



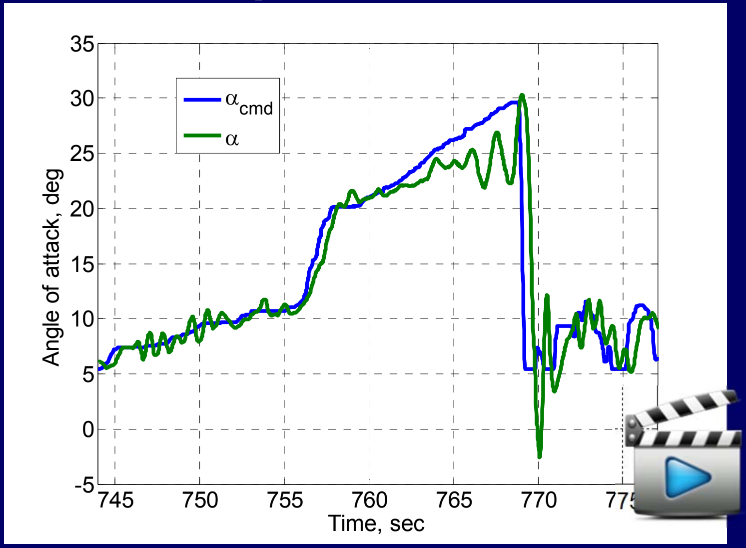
# $L_1$ Supports Large Flight Envelope Modeling

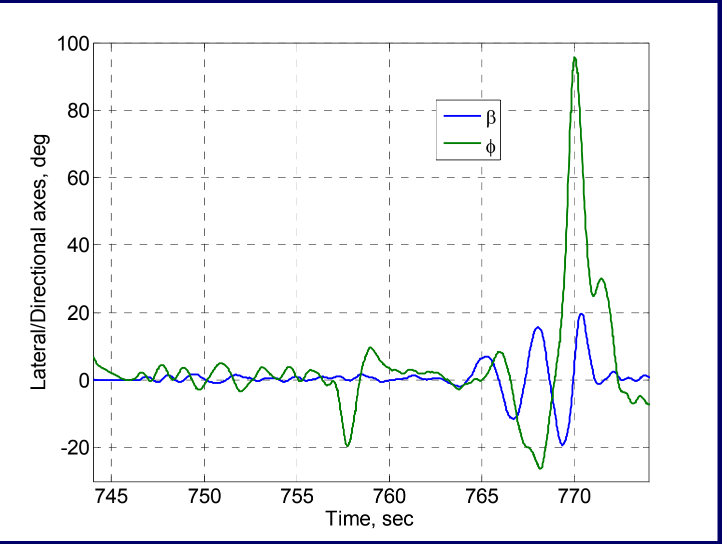
## *FLIGHTS 54, 55, 58*

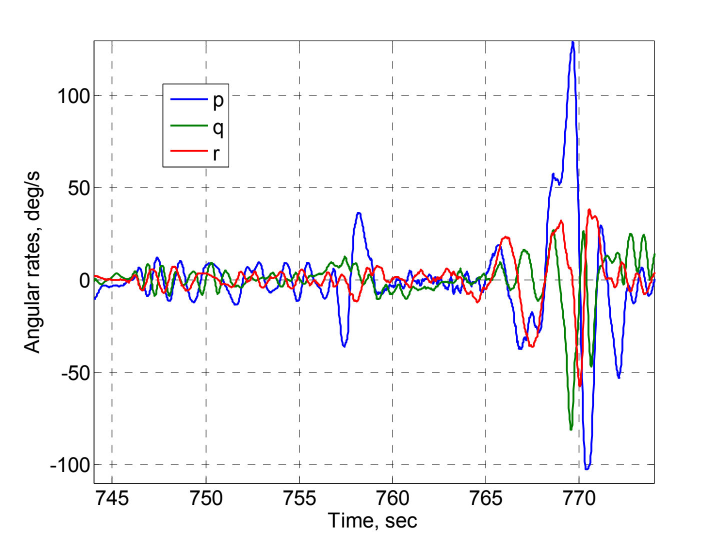


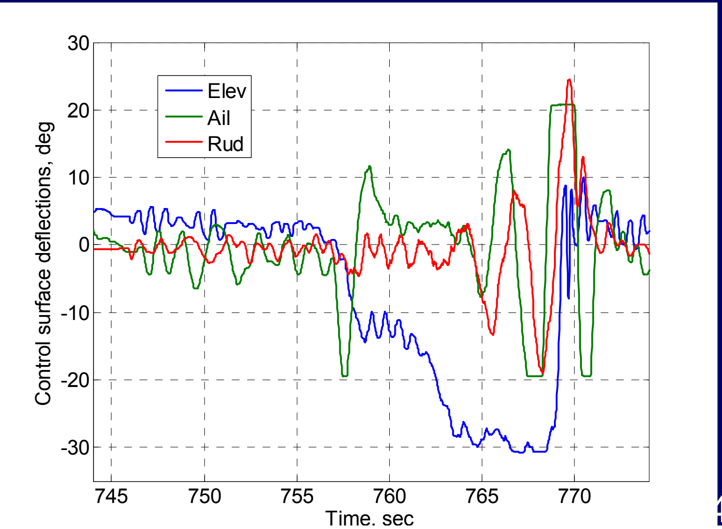
# AOA Pull Through Stall and Departure

- **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) |

Nominal

Neutrally Stable

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.**

# Media Attention: Flight International



NASA AIRSTAR

## Outside the box

NASA researchers are taking subscale models out of the windtunnel and into the atmosphere in a safety programme

**JOHN CROFT** FORT PICKET

To see the modern equipment and hear the dozen engineers and researchers prepping for the "show", the four-compartment portable operations centre we visited on 2 June could have been at the heart of any aeronautical flight-test programme about to carry people to the outer edges of the envelope.

A look at the video monitor in the top-left position of the command station console, showing the action happening outside the mobile operations station, painted the activity in a slightly different – and more relaxing – light, however. The aircraft outside was about to carry men and women to the outer edges of the envelope, but only vicariously.

We had travelled to Fort Picket airfield in Virginia on 2 June to witness test flight 19 of NASA's second "generic transport model", T2, a fully controllable, instrumented and dynamically scaled jet-powered – but unmanned – research aircraft, one of several used in the agency's airborne subscale transport aircraft research testbed (Airstar), a programme being run by the NASA Langley Research Center.

Airstar was developed in part to help define and augment the control properties of large transport type aircraft in unusual attitudes or post-stall orientations, upsets that have led to numerous loss-of-control accidents, but which are not tested on real aircraft for the obvious safety reasons.

While modern aircraft are designed to avoid such extreme pitch, roll and yaw environments, situations such as wake turbulence, sensor errors or other unintended consequences can lead to an upset for which pilots have not been prepared.

Airline pilot training today is largely based on full-flight simulators that are calibrated to a fairly limited flight-verified and windtunnel tested envelope. Since there is typically no data on which to model handling characteristics in extreme attitudes and post-stall regions, simulators and the pilots flying them can not train in that regime, creating a situation where pilots may experience a condition in flight for which they have not previously trained.

Two realistic methods are available for getting the data that could expand simulators into the upset regime – taking more windtunnel testing with a subscale model, or taking that subscale model out of the windtunnel and into the atmosphere. The latter is part of the genesis of Airstar, a "mobile in-flight windtunnel" built as part of NASA's aviation safety programme. Along with boosting the fidelity of simulators, Airstar is also being used as a rapid prototyping testbed for new flight-control algorithms, real-time parameter identification and integrated vehicle health management.

The 2 June T2 flights would focus on real-time parameter estimation and a University of Illinois flight-control algorithm designed to give pilots several seconds of control on an otherwise uncontrollable aircraft *(see P30)*. Flights would start with a safety pilot Lou Glaab, with standard radio control handheld controller, performing the take-off, followed by handover to research pilot Dan Murri sitting at the flightdeck control station in the mobile operations station, complete with standard flightdeck displays and synthetic vision. The mobile also has separate stations for engineering, communications and research.

Research pilots use test cards for the flights. Under NASA's unmanned air vehicle certificate of authorisation, T2 is required to stay within a 1 mile (1.6km) radius of the runway and below 2,500ft (760m). The safety pilot maintains eyes on the aircraft at all times and can intervene if there is a potential conflict with another aircraft. A typical flight includes 10-12 manoeuvres, says Murri. Adaptive control algorithms built by the George Institute Technology and the Massachusetts Institute of Technology were due to be tested as well.

T2 is not a typical radio-controlled aircraft. To match the aerodynamic performance of a »

**The research pilot station has standard displays with synthetic vision the primary view**


**Airstar is a "mobile in-flight windtunnel" built for NASA's aviation safety programme**





CIVIL SIMULATORS
SPECIAL REPORT

ADAPTIVE CONTROL

### BUYING PRECIOUS TIME

IN the emergency medical services field, experts speak of the "golden hour", the time within which a seriously wounded patient has a better chance of survival if rushed to an emergency room.

In a transport aircraft that has been upset, there is an equivalent concept when it comes to the potential for recovering control and saving many lives, except that the "hour" is actually "seconds". Engineers at the University of Illinois at Urbana-Champaign have developed an adaptive flight-control algorithm that could do just that – give the pilot of an otherwise uncontrollable aircraft just a few extra seconds of controllability, enough to give him or her time to save the vehicle from a loss-of-control accident.

NASA Langley researchers flew Illinois's L1 adaptive controller recently in its Airstar subscale flying testbed, putting the algorithm to the test during post-stall high angle-of-attack scenarios. Adaptive controls take advantage of every available control surface to follow the pilot's commands despite the state of the aircraft.

Langley senior researcher Irene Gregory explains that historically, adaptive control algorithms could guarantee stability in steady-state operations only, not during transients.

A new version of adaptive control called "L1", however, can predict transient behaviour. "That's a really big deal," says Gregory, "to know what will happen in the first seconds after a transient." NASA worked with Illinois to test the new algorithm on its subscale model to help research pilots maintain control of the aircraft when it departs the nominal operating envelope, a realm the device is intended to probe often. It is not too far of a leap to imagine such algorithms being used on commercial transport aircraft for the same purpose.

During testing of the T2 subscale generic transport model from 3-5 June at Fort Picket airfield in Virginia, the algorithm proved its worth. Gregory says one of the test cards called for the research pilot put the aircraft at a post-stall angle-of-attack without and then with the L1 controller. She explains that the research pilot's job was to put in step input of positive elevator at the post-stall AoA and attempt to hold the aircraft there. Without L1, "he couldn't hold the aircraft", she says. "It was rolling and slicing, exceeding 45° bank."

Using the L1 control law in the same manoeuvre however, she says the pilot was able to hold the nose-high attitude for 3-4s and bank angles never exceeding 20°. "It bought him time to make a proper recovery," she says. ■

**University of Illinois's algorithm proved its worth when testing T2 subscale aircraft**

» large transport aircraft, similar in shape to NASA's Boeing 757 test aircraft, the "generic transport model" weighs 25kg (54lb) to simulate a 90,720kg aircraft.

The small size also requires that the aircraft's 16 control surfaces respond more than four times faster than for the full-size aircraft. The model is scaled to about 5.5%, largely to match a windtunnel model for which NASA Langley has already tested. In addition, as a result of the scaling, aerodynamics results from the tests are considered valid only for mach numbers less than M0.45.

T2, with a 208cm (82in) wingspan, typically "cruises" at 85kt (157km/h) and 1,100ft (335m) on twin turbojet engines that produce 26lb thrust (0.115kN) each as it flies circular or figure-eight patterns in the test area between manoeuvres. On board is a redundant micro inertial reference system, air data probes on each wing tip and potentiometers to measure control surface movements. Commands from the research pilot in the mobile operations station are converted to control surface and engine commands and passed to the aircraft via radio frequency link.

Built into each of the planned test flights for the test campaign was a system identification process developed by Langley researcher Gene Morelli. Called Morelli sweeps, the process injects small control deflections to multiple surfaces simultaneously at different frequencies,

**With a simulated turbine whine humming in our headsets, operators performed full-power run-ups**

allowing researchers to quickly determine an aerodynamic representative model that, when joined with other models at other flight conditions, can be used to characterise an aircraft much faster than previously. A validated model could be used as the basis for a simulator that offers true upset recovery capability.

With test cards at the ready, operators divided between the mobile operations station and a work table near the runway's edge, initiated the engine starts. With a simulated turbine whine humming in our headsets in the mobile operations station, operators performed several full-power run-ups before giving technicians outside the go-ahead to carry T2 on to the runway centreline for take-off.

An out-of-range exhaust gas temperature signal from the left engine, however, scuttled the sortie. The team replaced the engine and repaired certain wiring harnesses for the next day's flight, a fix that was successful. Two flights were logged on the second day, and five on the final day, the highest number to date. ■

# What's next at NASA: bigger platforms

GTM (5.5%)

GMAT (15%)

TCM

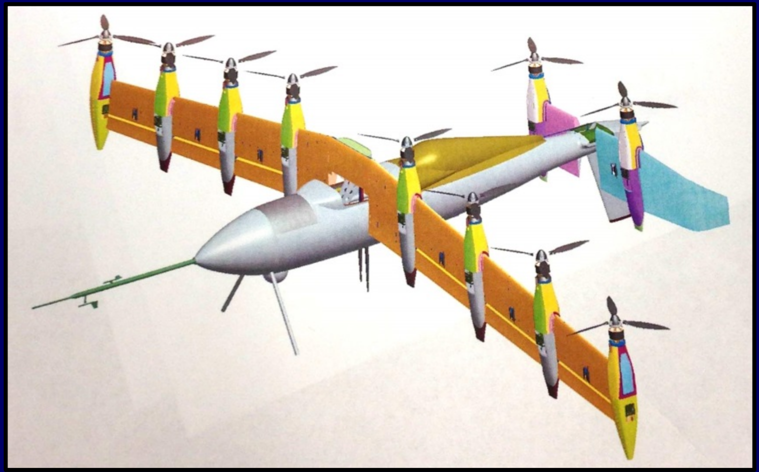
- **Autonomy:**
  - ✓ *Autonomous taxiing, take-off, up-and-away flight, and landing;*
  - ✓ *Pilot-in-the-loop FCLs for research tasks.*

# 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

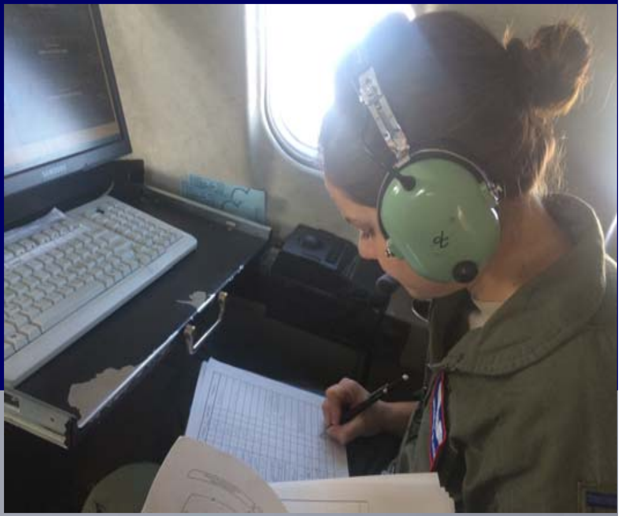
**BAT4**

# Learjet in Edwards AFB, March 2015

- Total of 19.6 hours of flight, approximately 14 hours of test on two conditions.
- Two flight conditions tested:
  - Up and Away (UA) 250 ±25 KCAS and 15,000 ±2000 feet pressure altitude.
  - Powered Approach with gear down and flaps 20 degrees at Vapp ±10 KCAS and 10,000 ±2000 feet pressure altitude.
  - Seven failure configurations, including F-100C Super Sabre Dance and lifting body configurations

# Inside the Aircraft

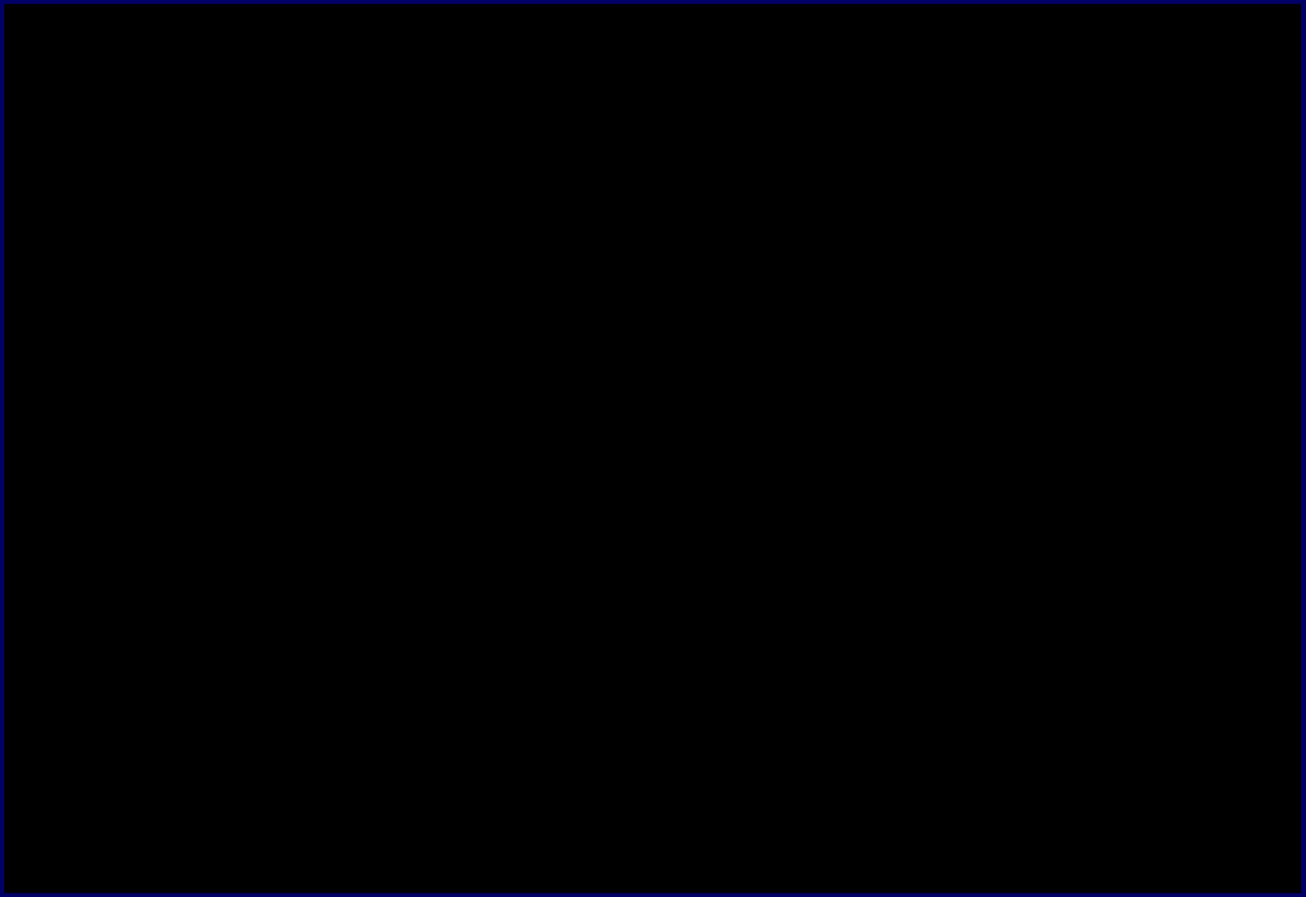





# Config E1- Coupled Roll, Spiral Mode Lifting Body Configuration

# Config D, “The Sabre Dance”

**Wing tips stall first, followed by the a/c shifting forward, pitch up moment increases, the ailerons become ineffective. Also Increased roll coupling, with High φ/β ratio and adverse  yaw is present.**

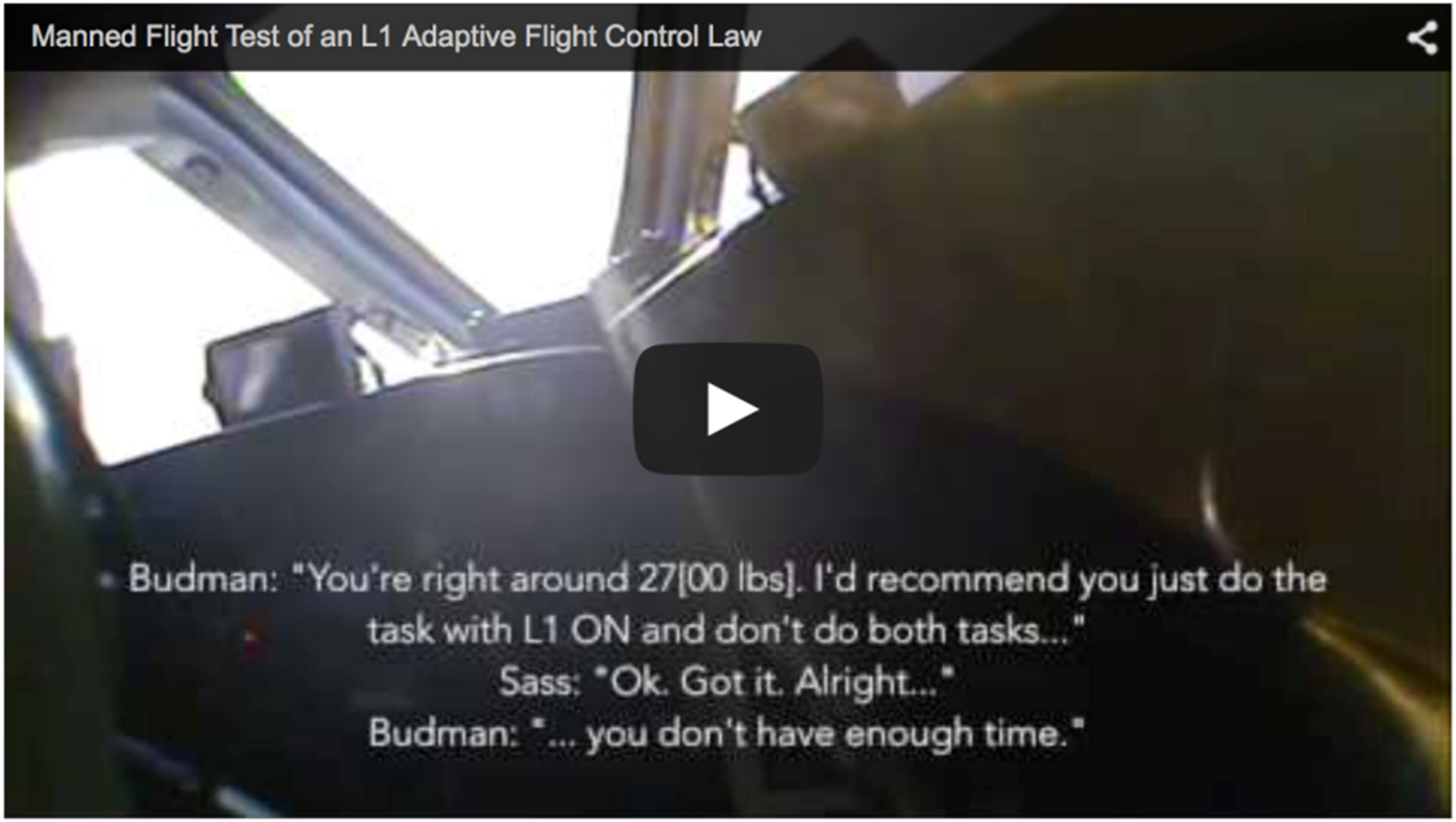


# 10 Sorties Flown, 1.8 hours each

- Sortie 1-2: Gain Margin and Time Delay, FQ
- Sortie 3-6: FQ/HQ, Landings
- Sortie 7-9: More FQ/HQ and Landings, Extra Configurations
- Sortie 10: L1 Version 2

| Monday | Tuesday | Wednesday | Thursday | Friday |
|---|---|---|---|---|
| February 23 | 24: Ground Checkout | 25 | 26: Ground Checkout | 27: Sortie 1<br>Sortie 2 |
| March 2 | 3: Sortie 3<br>Sortie 4 | 4: Sortie 5<br>Sortie 6 | 5: Sortie 7<br>Sortie 8<br>→<br>→ | 6: Sortie 9<br>Sortie 7 |
| 9: Sortie 10<br>Sortie 8<br>Sortie 9 | 10: Sortie B/U<br>Sortie 10 | 11: Sortie B/U | 12: Sortie B/U | 13: Sortie B/U |

# In Cockpit Video of L1 Testing



# USAF Test Pilots School Vets Safer Adaptive Flight Controller

Guy Norris | *Aviation Week & Space Technology* *Apr 6, 2015*



"The L1 controller is designed to automatically intervene in the case of control problems, immediately reconfiguring the flight control system to compensate for degraded flying qualities from mechanical failure or battle damage to a control surface, or even the unintended result of shifting center-of-gravity inflight for better cruise performance. Acting as a backup to the standard flight control system, the L1 is designed to provide safe, predictable, reliable and repeatable responses that would free up pilots to deal with the emergency and further compensate for reduced performance."

# Other Craft in Europe


DA-42 (TUM)

Generic helicopter model

Hexarotor

Gripen-like fighter (SAAB)


Cessna Citation II (TUD)

Generic Missile Model

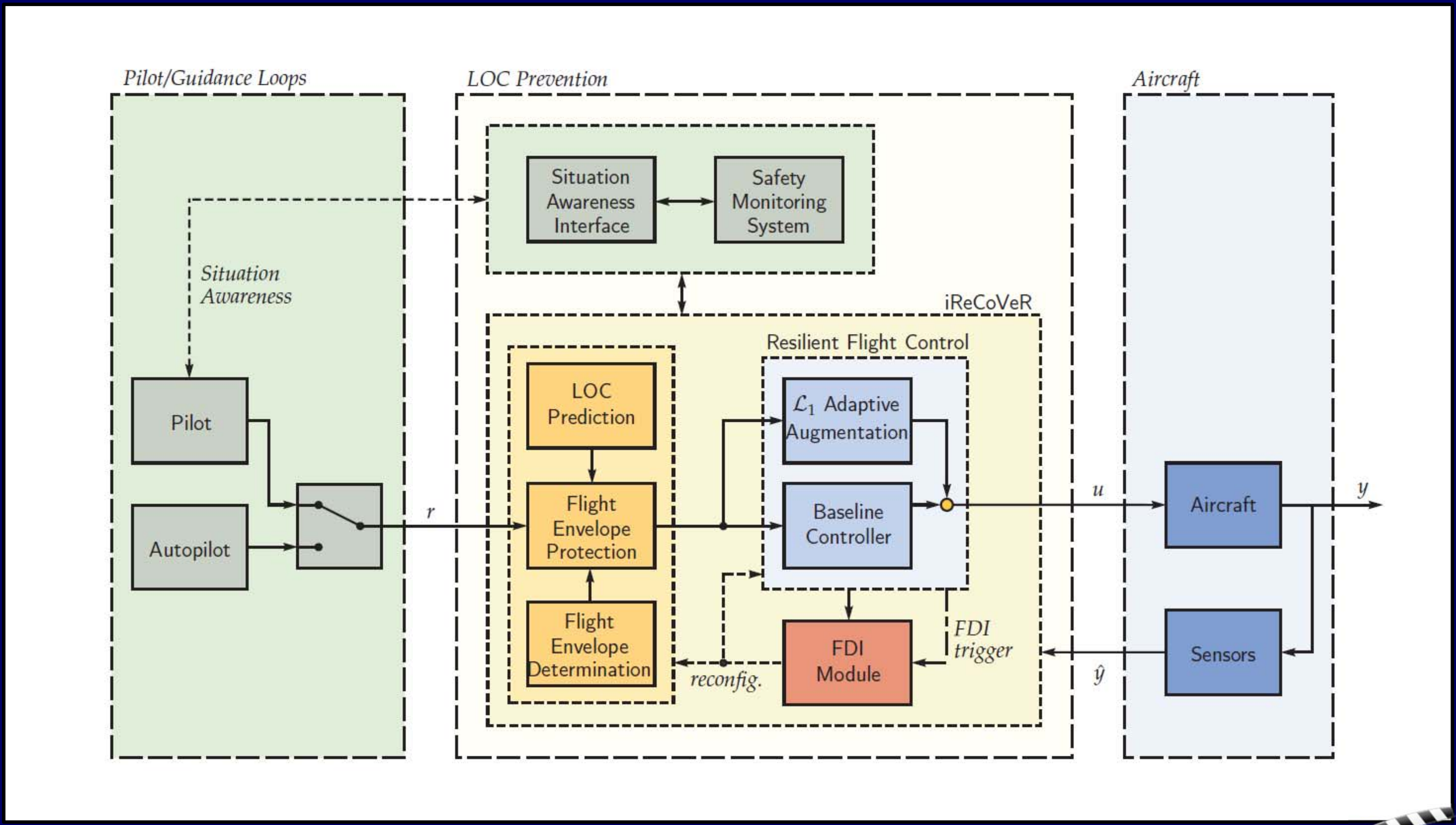
Quad (TUM)

Quad

Photocopter

# NASA: iReCoVeR Architecture

- **Integrated architecture for Loss-of-Control prevention**:




- **iReCoVeR**: integrated **Re**configurable **Co**ntrol for **Ve**hicle **R**esilience
- L1Simplex; situation awareness interfaces; etc.

# $L_1$ in Other Application Domains

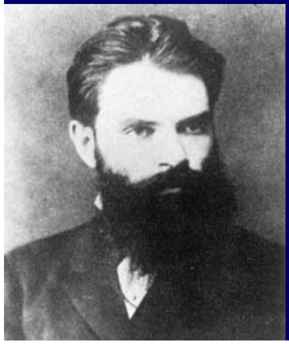
- $L_1$ control of  boats (Raymarine, UK, Evolution autopilots) – commercially available
- $L_1$ control of  smart drones (IntelinAir) – commercially available
- $L_1$ control of  Learjet (Calspan, Edwards AF base)
- $L_1$ control of  hydraulic pumps (Caterpillar, USA)
- $L_1$ control of drilling pressure (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, a model helicopter and a missile (TU of Munich, Germany & industries)
- $L_1$ 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) and rotorcraft  (Jon How, MIT)

# Conclusions

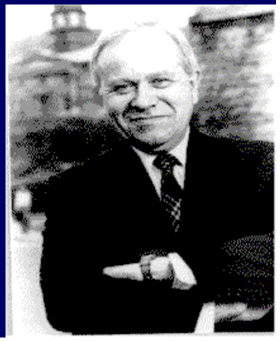
- What do we need to know?
  - Boundaries of uncertainties → sets the filter bandwidth
  - CPU (hardware) → sets the adaptive gain

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!*



# Acknowledgments

My group:

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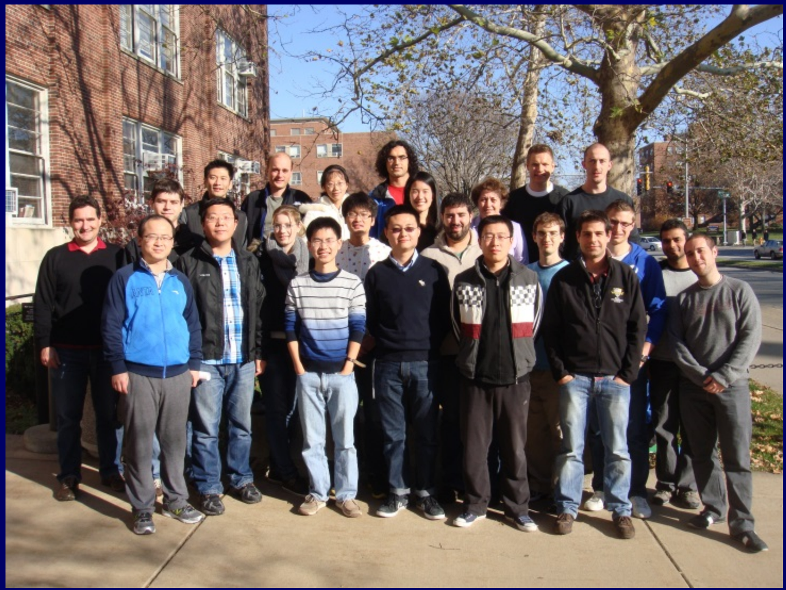
- ❑ Jan Vervoorst (Ph.D. student IESE)
- ❑ Yue Ding (Ph.D. student ME)
- ❑ Steven Snyder (Ph.D. student ME)
- ❑ Steven Pelech (Ph.D. student ME)
- ❑ June Chongvisal (MS. Student ECE)
- ❑ Kasey Ackerman (MS. Student ME)
- ❑ Steven Pelech (MS. Student ME)
- ❑ Javier Puig Navarro (Ph.D. student AE)



Collaborations that were instrumental:

- ❑ **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.youtube.com/user/nhovakimgroup**

**http://www. IntelinAir.com**