The Theory of Fast and Robust Adaptation
L_1 Adaptive Control

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A. M. Lyapunov
1857-1918

LCCC workshop April 21-23, 2010
Lund University, Sweden

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
- Aerospace Applications
  - NPS flight tests
  - AirSTAR flight tests (IRAC, NASA)
- Networked control systems
  - NPS flight tests
- 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
  - Nov. 15, 1967, X-15A-3

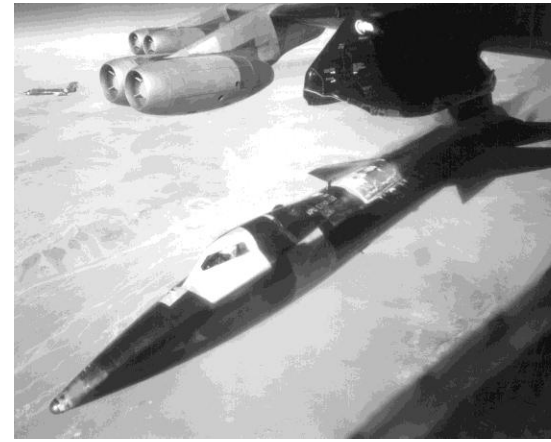
First Flight Test in 1967

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

X-15 in Flight Air Force Photo Date Unknown

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: E-4935   Date: 1959   Photo by: NASA

X-15 Mated to B-52 Captive Flight



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

Crash site of the 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, Wittenmark, Morse, Narendra, Landau, Goodwin, Keisselmeier, Anderson, et al.
- Robustness issues, instability (early 1980s)
  - Egardt, Ioannou, Stein, Athans, Valavani, Rohrs, Anderson, Sastry, et al.
- Robust Adaptive Control (1980s)
  - Ioannou, Praly, Tsakalis, Sun, Tao, Datta, Middleton, Basar, et al.
- Nonlinear Adaptive Control (1990s)
  - Adaptive Backstepping, Neuro, Fuzzy Adaptive Control
    - Krstic, Kanelakopoulos, Kokotovic, Zhang, Ioannou, Narendra, Ioannou, Lewis, et al.

- Search methods, multiple models, switching techniques (1990s)
  - Martenson, Miller, Barmish, Morse, 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 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?

Main Features of L_1 Adaptive Control

- **Separation (decoupling) between adaptation & robustness**
- **Performance limitations consistent with hardware limitations**
- Guaranteed **fast adaptation**
- Guaranteed **transient response** for system's **input and output**
  - **NOT** achieved via **persistence of excitation** **or** **gain-scheduling**
- Guaranteed (bounded away from zero) **time-delay margin**
- Uniform **scaled transient response** dependent on changes in initial conditions, unknown parameters, and 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: Fast and robust adaptation with continuous feedback!

Red Flags Raised in Literature

- **Brian Anderson's quote*:**

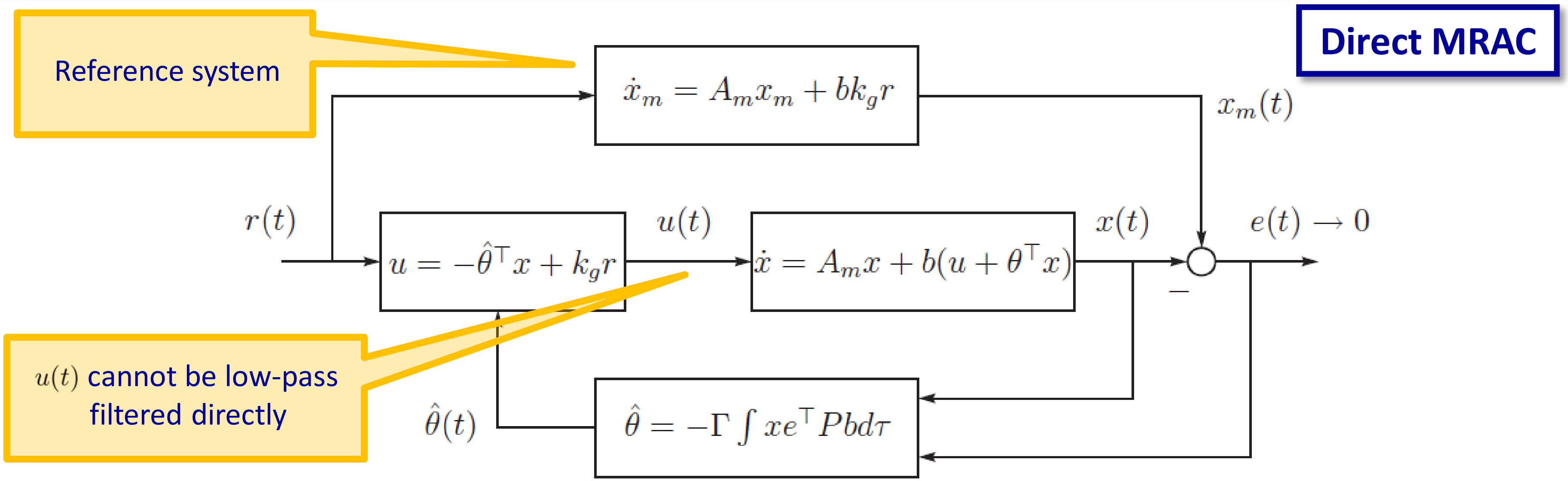
> *"The notion of having a flag in an adaptive control algorithm to indicate the inappropriateness of an originally posed objective is practically important, and missing from older adaptive control literature. Logic really demands it. If a plant is initially unknown or only partially unknown, a designer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

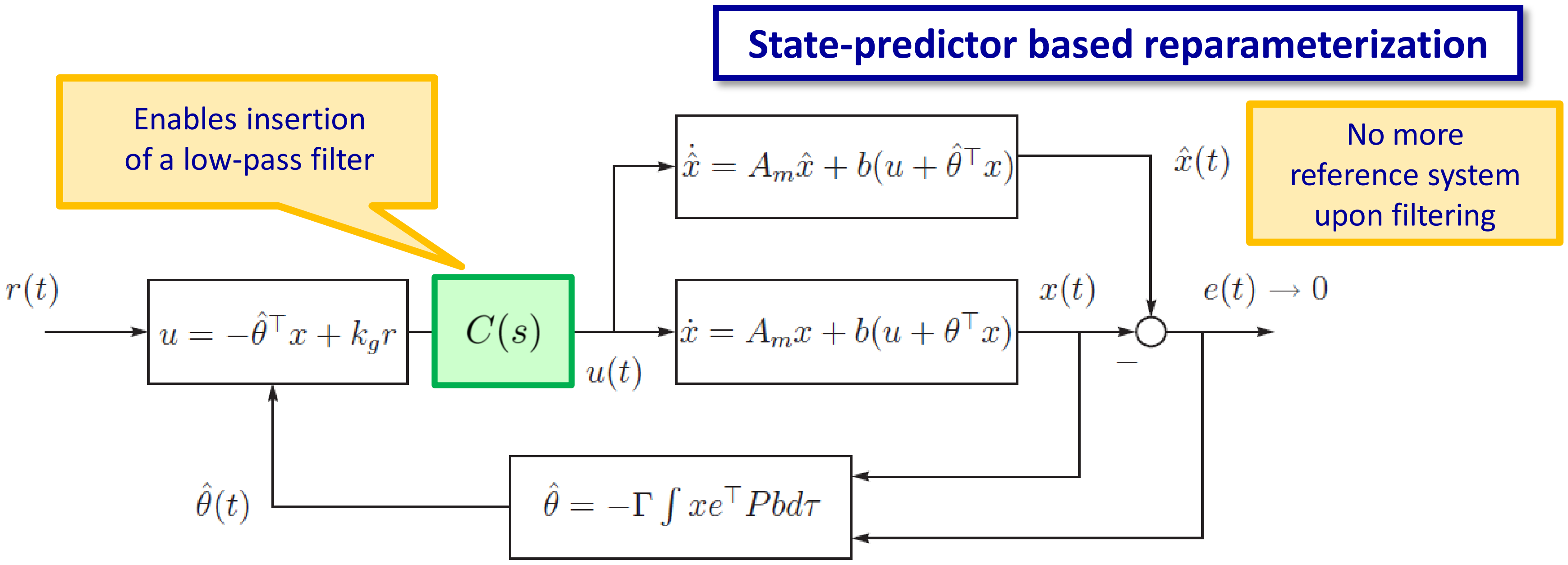
* **"Failures of Adaptive Control Theory",**
COMMUNICATIONS IN INFORMATION AND SYSTEMS, Vol. 5, No. 1, pp. 1-20, 2005

Dedicated to Prof. Thomas Kailath on his 70th Birthday

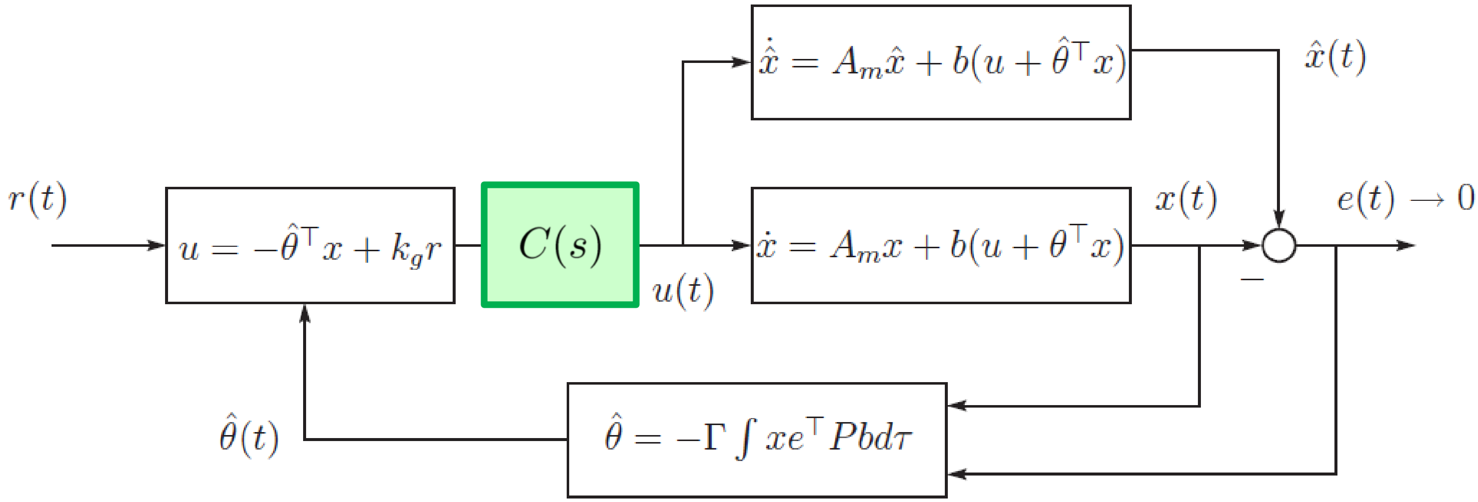
1. Fekri, Athans, and Pascoal, "Issues, Progress and New Results in Robust Adaptive Control", International Journal on Adaptive Control and Signal Processing, March 2006
2. B. Anderson, Challenges of adaptive control: past, permanent and future, Annual Reviews in Control, pages 123-125, December, 2008

Two Equivalent Architectures of Adaptive Control





Stability and Asymptotic Convergence



- Closed-loop: $$s\hat{x}(s) = A_m \hat{x}(s) + b\left((1 - C(s))\left\{\hat{\theta}^\top(t) x(t)\right\} + C(s) k_g r(s)\right)$$

➢ Solving: $$\hat{x}(s) = (s\mathbb{I} - A_m)^{-1} b\left((1 - C(s))\left\{\hat{\theta}^\top(t)(\hat{x}(t) - e(t))\right\} + C(s) k_g r(s)\right)$$

bounded

- Sufficient condition for stability:

$$\left\| (1 - C(s))(s\mathbb{I} - A_m)^{-1} b \right\|_{\mathcal{L}_1} L < 1$$

⇒

$$\lim_{t \to \infty} (\hat{x}(t) - x(t)) = 0$$

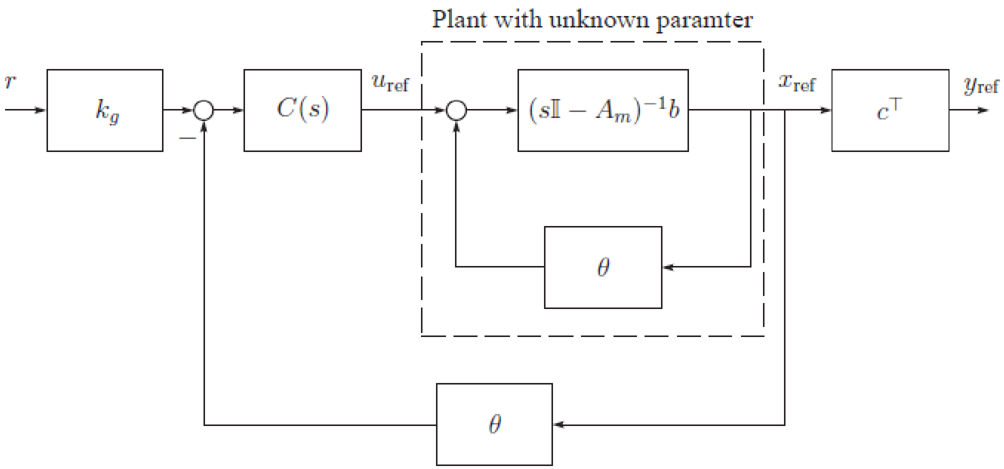
(Barbalat's Lemma)

Closed-Loop Reference System

- Filtered ideal controller: $u_{\text{ref}}(s) = C(s)u^*(s)\,, \quad u^*(t) = -\theta^\top x_{\text{ref}}(t) + k_g r(t)$
- Closed-loop:

$$\begin{aligned} s x_{\text{ref}}(s) &= A_m x_{\text{ref}}(s) \;+\; b\left(u_{\text{ref}}(s) + \theta^\top x_{\text{ref}}(s)\right) \\ &= A_m x_{\text{ref}}(s) + b\left((1 - C(s))\theta^\top x_{\text{ref}}(s) + C(s) k_g r(s)\right) \end{aligned}$$

$$x_{\text{ref}}(s) = (s\mathbb{I} - A_m)^{-1} b\left((1 - C(s))\theta^\top x_{\text{ref}}(s) + C(s) k_g r(s)\right)$$



Closed-loop Reference System

- Sufficient condition for stability:

$$\left\| (1 - C(s))\,(s\mathbb{I} - A_m)^{-1} b \right\|_{\mathcal{L}_1} L \;<\; 1$$

$C(s) = 1$ ⇒ **Reference System of MRAC**

Guaranteed Adaptation Bounds: SCALING

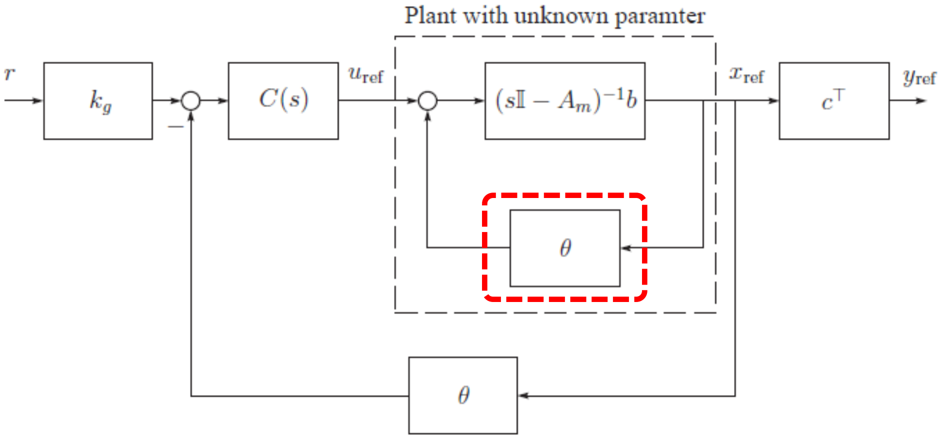
- System state: $$\|x - x_{\text{ref}}\|_{\mathcal{L}_\infty} \leq \frac{\gamma_1}{\sqrt{\Gamma}}$$ $$\lim_{\Gamma\to\infty} \|x - x_{\text{ref}}\|_{\mathcal{L}_\infty} = 0$$
- System input: $$\|u - u_{\text{ref}}\|_{\mathcal{L}_\infty} \leq \frac{\gamma_2}{\sqrt{\Gamma}}$$ $$\lim_{\Gamma\to\infty} \|u - u_{\text{ref}}\|_{\mathcal{L}_\infty} = 0$$

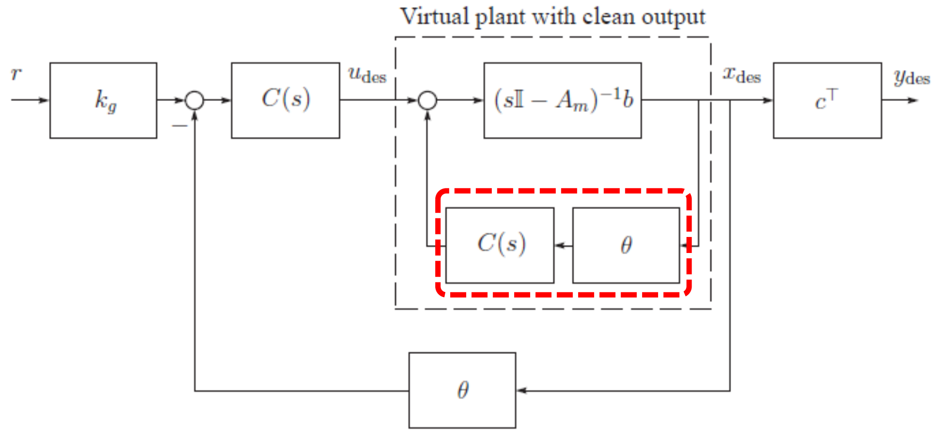
$$\gamma_2 = \left\| C(s)\frac{1}{c_0^\top (s\mathbb{I} - A_m)^{-1} b} c_0^\top \right\|_{\mathcal{L}_1} \sqrt{\frac{\theta_m}{\lambda_{\min}(P)}} + \|C(s)\|_{\mathcal{L}_1} L\gamma_1$$

MRAC: $C(s) = 1 \quad \Rightarrow \quad \gamma_2 \to \infty$

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

LTI System for Control Specifications





Closed-loop Reference System
achieved via fast adaptation

Design System
for defining control specs

- Closed-loop reference system:

$$y_{\mathrm{ref}}(t) = c^\top \left[\mathbb{I} - (1 - C(s))\,(s\mathbb{I} - A_m)^{-1}\, b\theta^\top\right]^{-1} (s\mathbb{I} - A_m)^{-1}\, bC(s)\,\{k_g r(t)\}$$

- Design system:

$$y_{\mathrm{des}}(t) = \underbrace{c^\top (s\mathbb{I} - A_m)^{-1}\, bC(s)k_g}_{M(s)}\,\{r(t)\}$$

Independent of the unknown parameters

Guaranteed Robustness Bounds

- **Achieving desired specifications:**
  - System output: $$\|y_{\text{ref}} - y_{\text{des}}\|_{\mathcal{L}_\infty} \leq \frac{\lambda}{1-\lambda} \|c^\top\|_{\mathcal{L}_1} \left\|k_g \left(s\mathbb{I} - A_m\right)^{-1} bC(s)\right\|_{\mathcal{L}_1} \|r\|_{\mathcal{L}_\infty}$$
  - System input: $$\|u_{\text{ref}} - u_{\text{des}}\|_{\mathcal{L}_\infty} \leq \frac{\lambda}{1-\lambda} \|C(s)\theta^\top\|_{\mathcal{L}_1} \left\|k_g \left(s\mathbb{I} - A_m\right)^{-1} bC(s)\right\|_{\mathcal{L}_1} \|r\|_{\mathcal{L}_\infty}$$
- **Sufficient condition for stability:**

$$\lambda = \left\|(1 - C(s))(s\mathbb{I} - A_m)^{-1} b\right\|_{\mathcal{L}_1} L < 1$$

- **Performance improvement:**

$$\lambda \rightarrow \min$$

Guaranteed (*Uniform and Decoupled*) Performance Bounds

- Use large adaptive gain (sΓaling):

$$\|y - y_{\text{ref}}\|_{\mathcal{L}_\infty} \leq \mathcal{O}\left(\frac{1}{\sqrt{\Gamma}}\right) \qquad \|u - u_{\text{ref}}\|_{\mathcal{L}_\infty} \leq \mathcal{O}\left(\frac{1}{\sqrt{\Gamma}}\right)$$

- Design $C(s)$ to render λ sufficiently small (trade-off robustness for performance) :

$$\|y_{\text{ref}} - y_{\text{des}}\|_{\mathcal{L}_\infty} \leq \mathcal{O}(\lambda) \qquad \|u_{\text{ref}} - u_{\text{des}}\|_{\mathcal{L}_\infty} \leq \mathcal{O}(\lambda)$$

Decoupling of Adaptation from Robustness

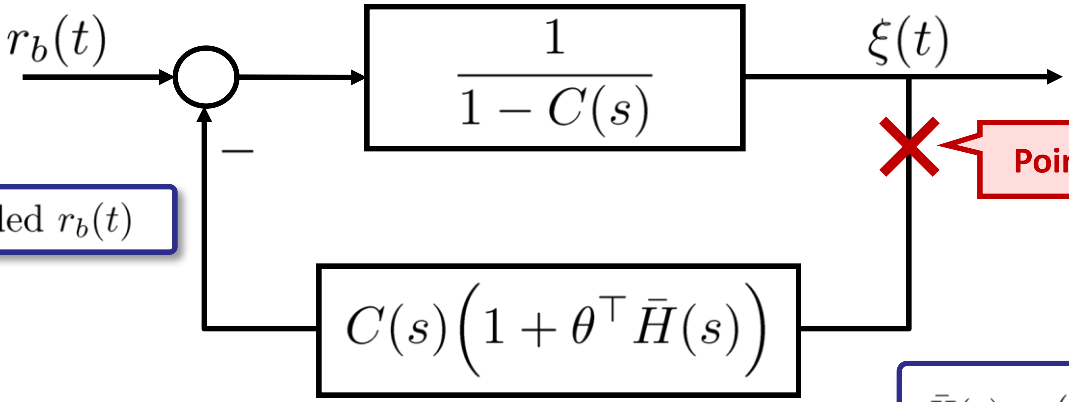
$$\|y - y_{\text{des}}\|_{\mathcal{L}_\infty} \leq \mathcal{O}\left(\frac{1}{\sqrt{\Gamma}}\right) + \mathcal{O}(\lambda) \qquad \|u - u_{\text{des}}\|_{\mathcal{L}_\infty} \leq \mathcal{O}\left(\frac{1}{\sqrt{\Gamma}}\right) + \mathcal{O}(\lambda)$$

Large adaptive gain → Smaller step-size → Faster CPU

* **Remark:** Sensor and control sampling can be done at a lower rate

Time-Delay Margin and Gain Margin

- **Time-delay margin:**



$C(s) = 1 \Rightarrow$ unbounded $r_b(t)$

Point Time-delay occurs

Plant

$\bar{H}(s) = \left(s\mathbb{I} - A_m - b\theta^\top\right)^{-1} b$

$$\exists \Gamma_0\,, \quad \Gamma_0 < \Gamma \quad \Rightarrow \quad \tau_{\text{margin}} \geq \tau_m\left(H(s)\right)$$

Lower bound for the **time-delay margin**

where $H(s) = \dfrac{C(s)\left(1+\theta^\top \bar{H}(s)\right)}{1-C(s)}$

- **Gain margin:**

$$\mathcal{G}_m = [\omega_\ell\,, \; \omega_u]$$

Projection defines the **gain margin**

Main Result

- If $\left\|(1-C(s))(s\mathbb{I}-A_m)^{-1}b\right\|_{\mathcal{L}_1} L < 1$, then the L_1 adaptive controller ensures **uniform transient and steady-state performance bounds**:

$$\|x - x_{\text{ref}}\|_{\mathcal{L}_\infty} \leq \mathcal{O}\left(\frac{1}{\sqrt{\Gamma}}\right) \qquad \|u - u_{\text{ref}}\|_{\mathcal{L}_\infty} \leq \mathcal{O}\left(\frac{1}{\sqrt{\Gamma}}\right)$$

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

$$\tau_{\text{margin}} \geq \tau_m\left(H(s)\right) > 0$$

where τ_m is the time-delay margin of an LTI system. The **gain margin** can be arbitrarily improved by increasing the domain of projection.

Design Philosophy

- <u>Adaptive gain:</u> as large as CPU and sensors permit (**fast adaptation**)
  - ✓ Fast adaptation ensures arbitrarily close tracking of the auxiliary closed-loop reference system with **bounded away from zero time-delay margin**.

Fast adaptation leads to improved performance and improved robustness

- <u>Low-pass filter:</u>
  - ✓ Defines the trade-off between **performance** and **robustness**
  - ✓ Increase the **bandwidth of the filter**:
    - ➢ The auxiliary closed-loop reference system can approximate arbitrarily closely the ideal desired reference system
    - ➢ Leads to reduced time-delay margin

Tracking vs Robustness can be analyzed analytically

Performance can be predicted a priori

Time-Delay Margin: MRAC and L_1 for a PI Controller

MRAC

$$\dot{x}(t) = -x(t) + u(t) + \theta$$

L_1

- Loop transfer functions in the presence of time-delay:

$$L(s) = \frac{\Gamma}{s(s+1)} e^{-\tau s}$$

$$L(s) = \frac{C(s)\Gamma}{s^2 + s + (1 - C(s))\Gamma} e^{-\tau s}$$

- Time-delay margin τ^* : $\exists \omega^*$

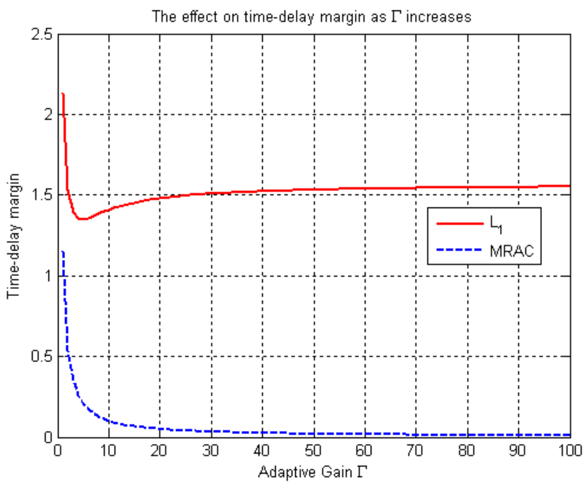
$$L(j\omega^*) = \frac{\Gamma}{j\omega^*(j\omega^*+1)} e^{-j\tau^*\omega^*} = -1$$

$$\tau^*(\Gamma) = \frac{\angle L(j\omega^*)}{\omega^*} \to 0 \quad \text{as} \quad \Gamma \to \infty$$

- Time-delay margin τ^* : $\exists \omega^*$

$$L(j\omega^*) = \frac{\Gamma}{j\omega^*(j\omega^*+1)^2 + j\omega^*\Gamma} e^{-j\tau^*\omega^*} = -1$$

$$\tau^*(\Gamma) = \frac{\angle L(j\omega^*)}{\omega^*} \to \frac{\pi}{2} \quad \text{as} \quad \Gamma \to \infty$$



- Application of nonlinear L_1 theory:

$$C(s) = \frac{1}{s+1}, \quad \tau_m = \frac{\pi}{2}$$

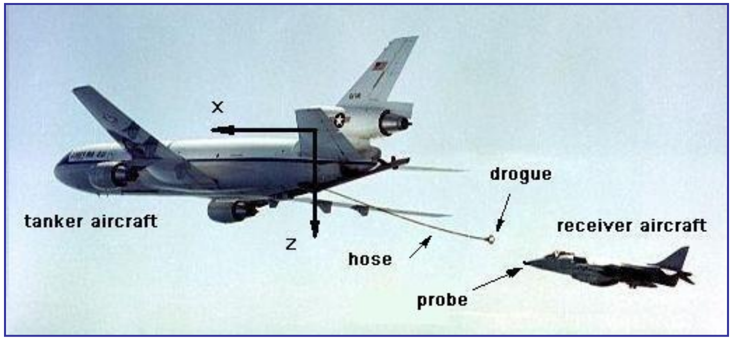
$$\lim_{\Gamma \to \infty} \tau^* = \tau_m$$

Extensions 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
  - …

- **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

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

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

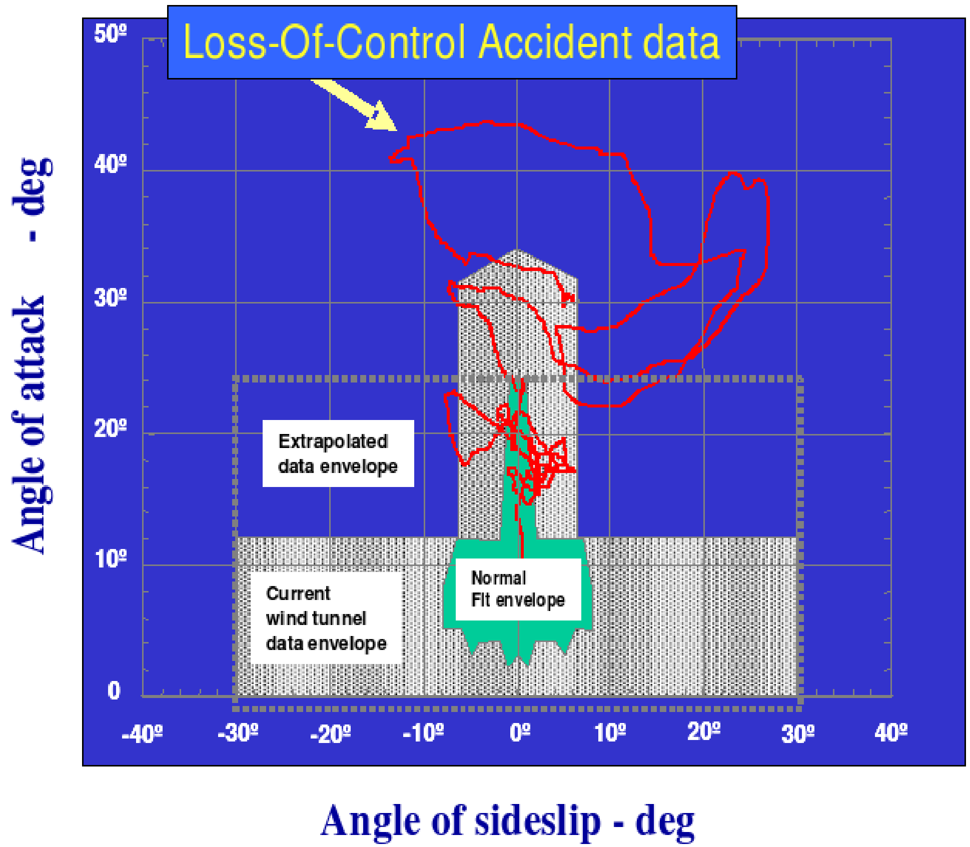
Integrated Resilient Aircraft Control (IRAC)

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.

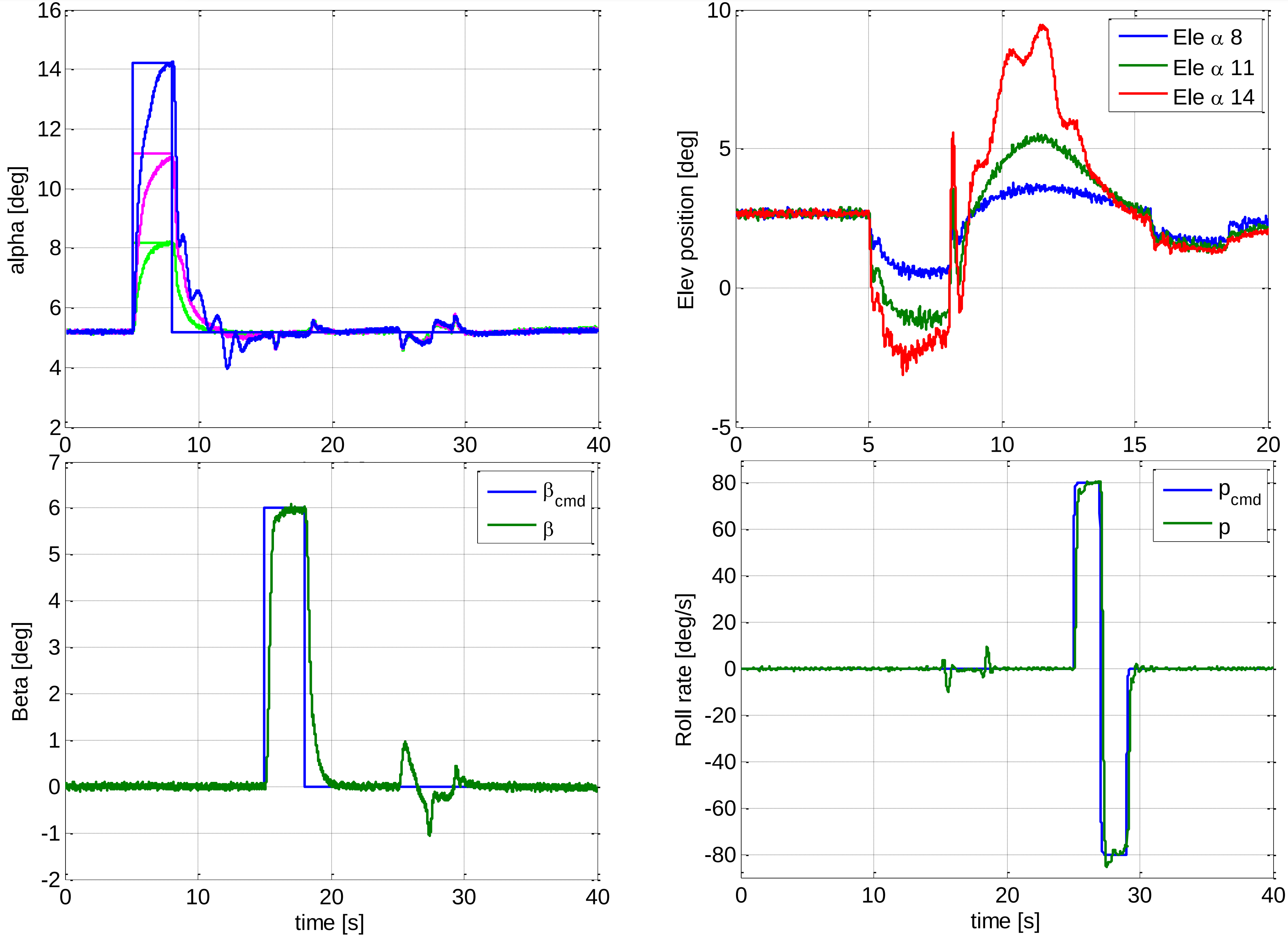
- 5.5 % geometrically and dynamically scaled model
  - 82in wingspan, 96 in length, 49.6 lbs (54 lbs full), 53 mph stall speed
  - Model angular response is 4.26 faster than full scale
  - Model velocity is 4.26 times slower than regular scale

Controlling High-α Regimes…

Stall…
Nose-slice roll-off…
Recovery…

Control aircraft in stall and post-stall regimes!

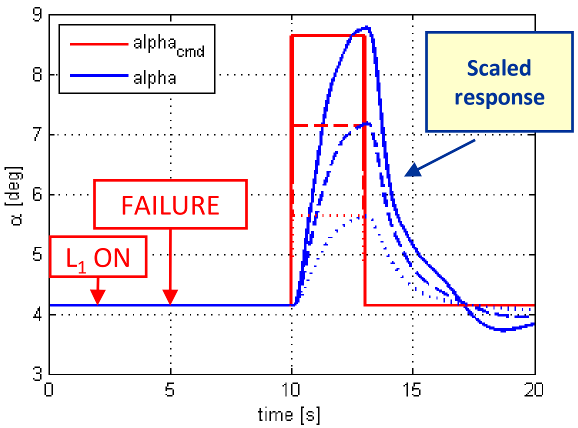
AirSTAR :: Batch Sims (*Healthy UAV*)



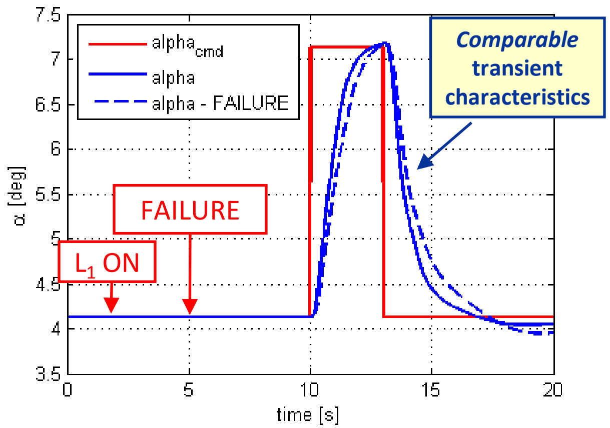
AirSTAR :: Batch Sims (*Impaired UAV*)

Outboard elevators stuck at trim

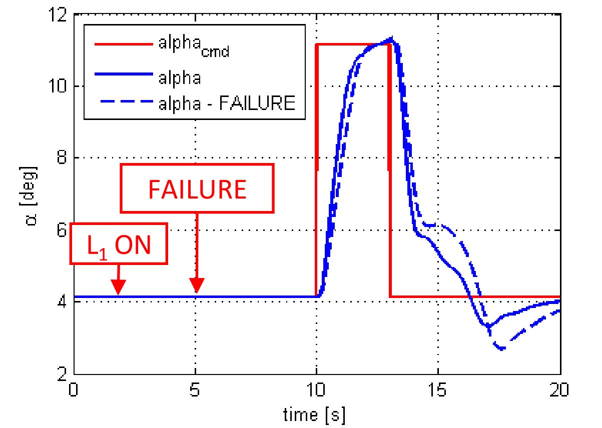
Impaired UAV	Healthy vs Impaired UAV (*normal* flight conditions)	Healthy vs Impaired UAV (stall regimes: <40knots)



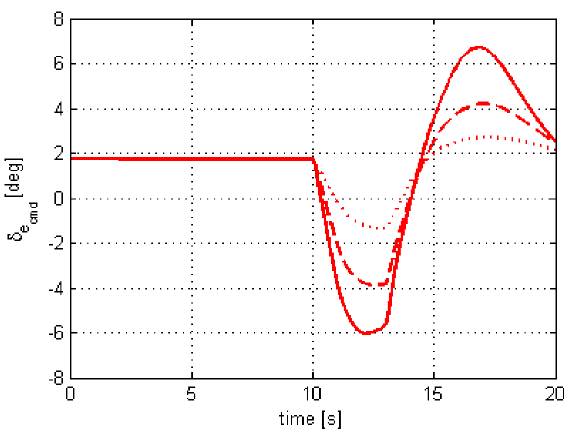
Angle of attack



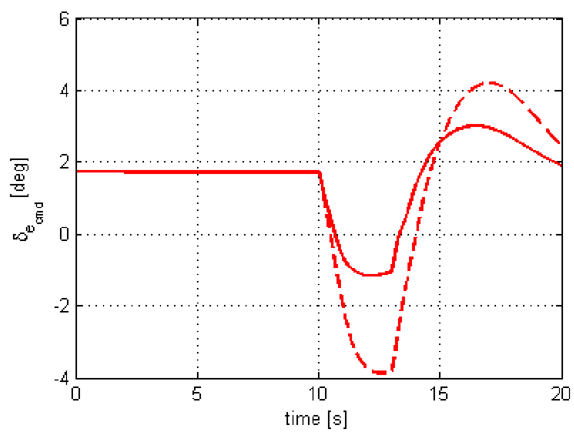
Angle of attack



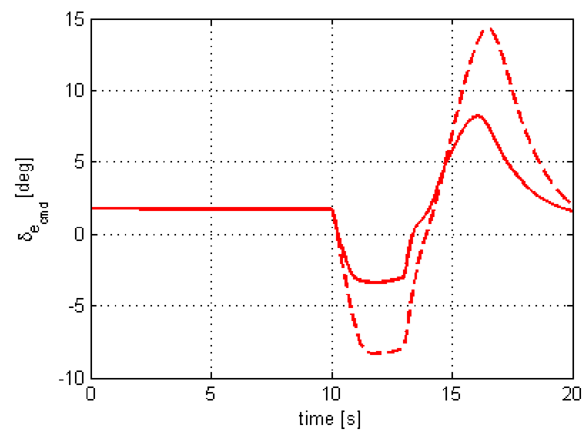
Angle of attack



Elevator deflection



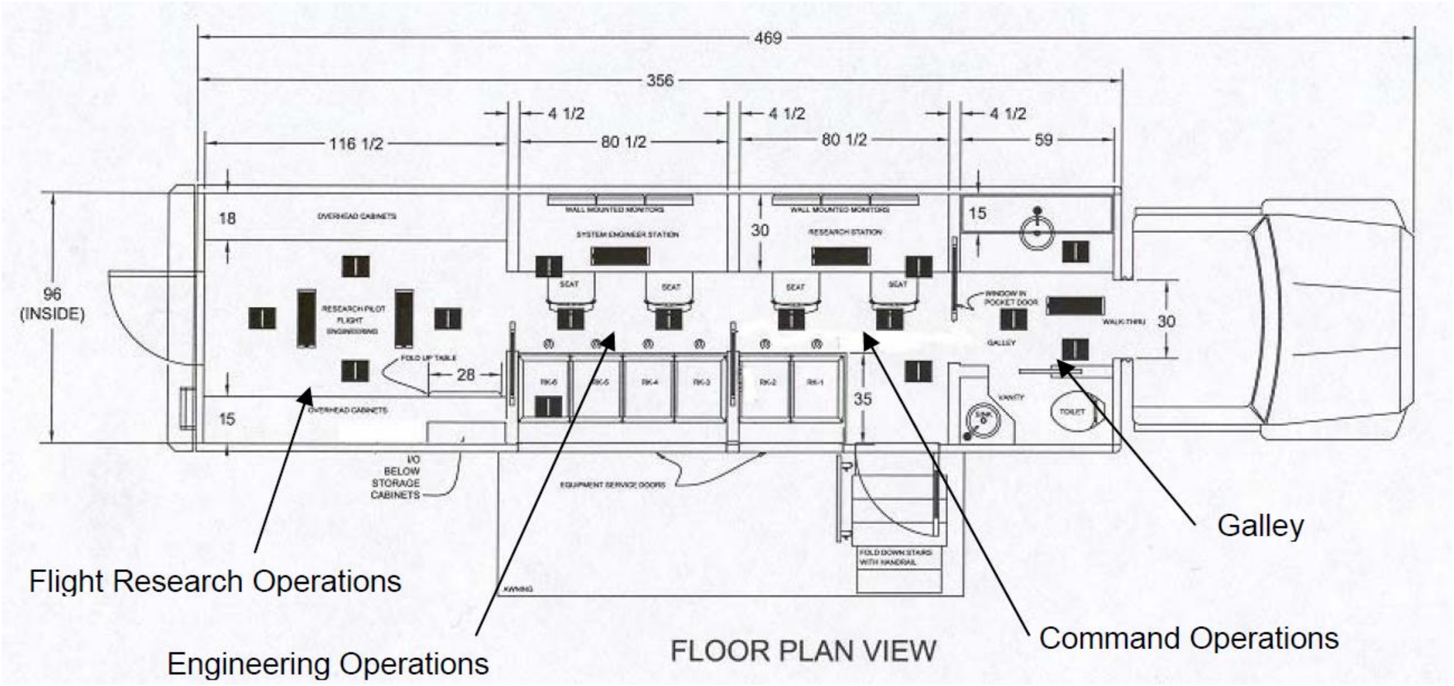
Elevator deflection



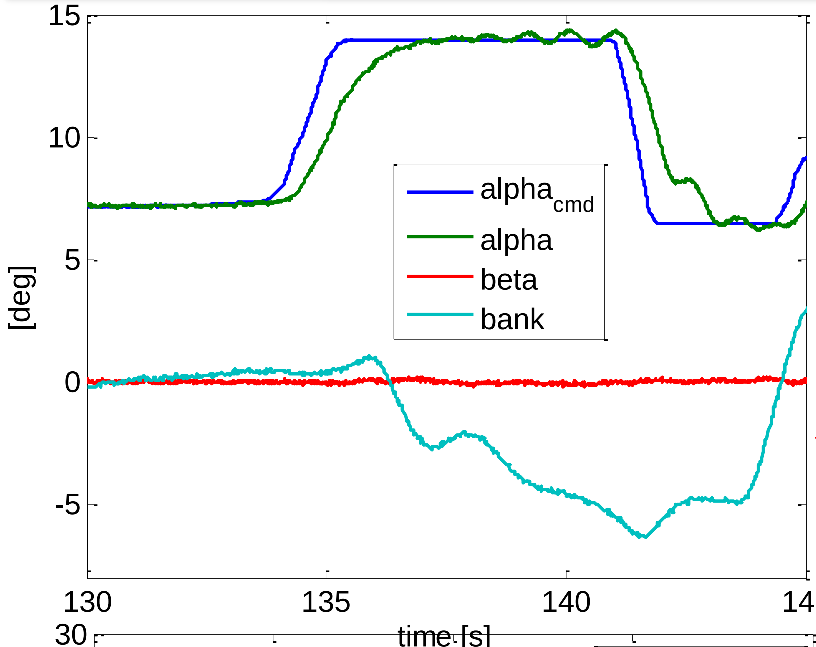
Elevator deflection

Pre-Flight and Check-List

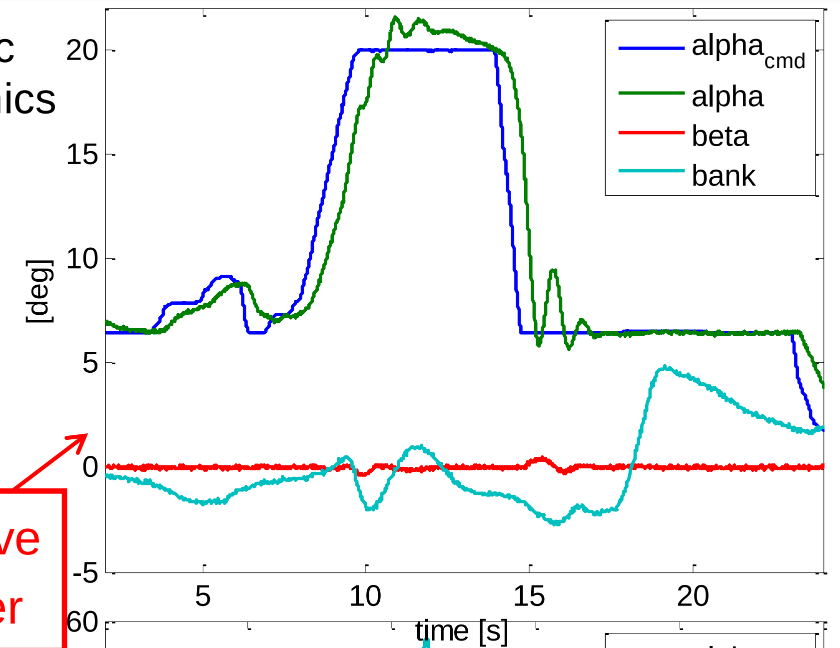
Mobile Operations Station



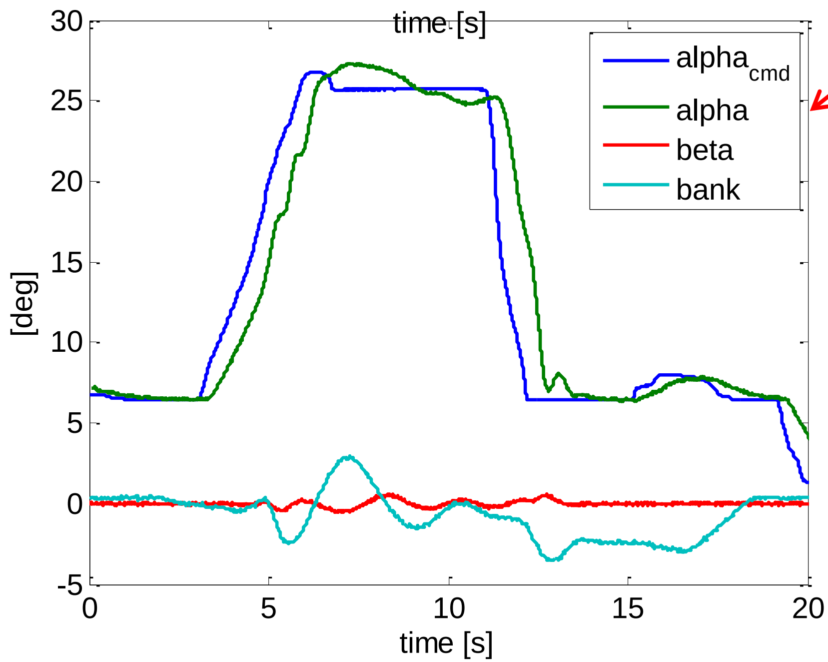
AirSTAR :: Piloted Task (*AoA capture – high α*)



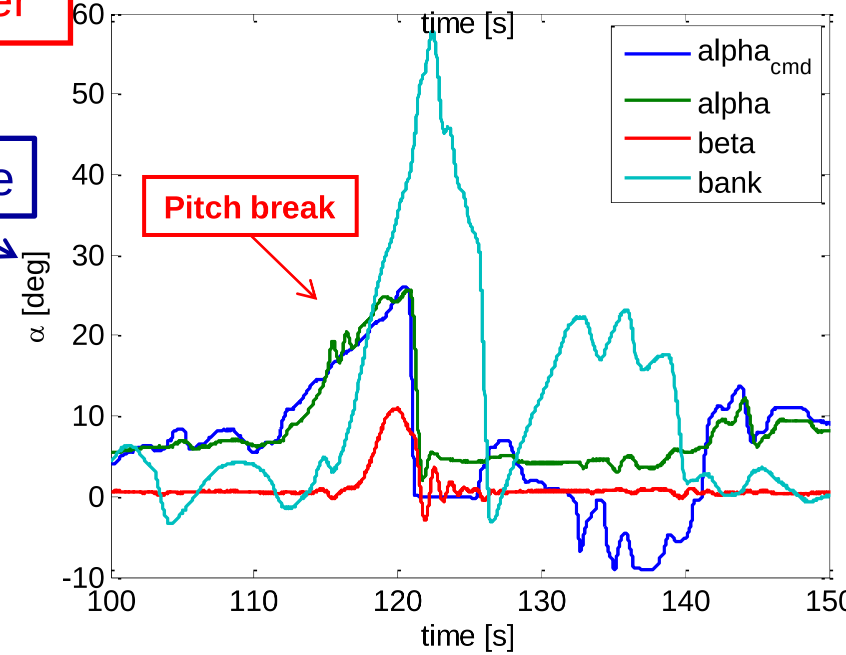
- Asymmetric aerodynamics
- Low Clp
- Roll off
- Noseslice



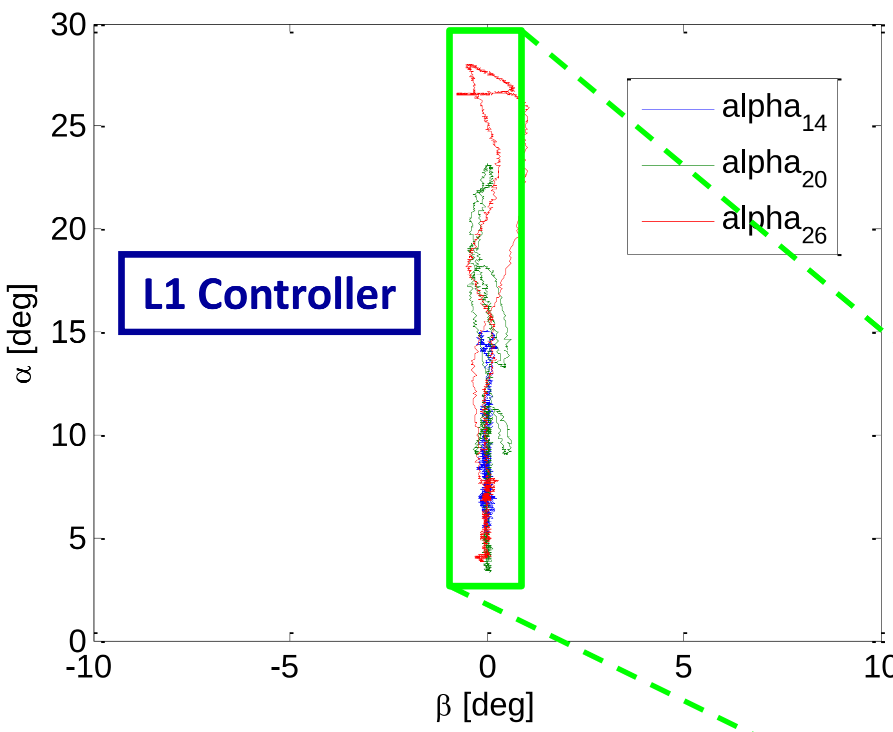
L_1 Adaptive Controller

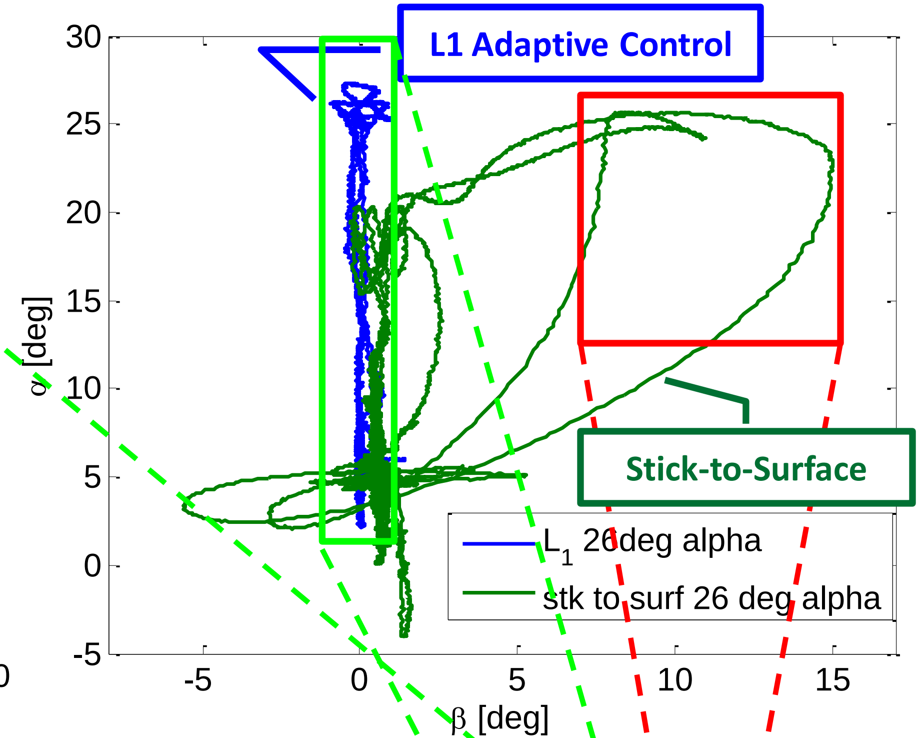


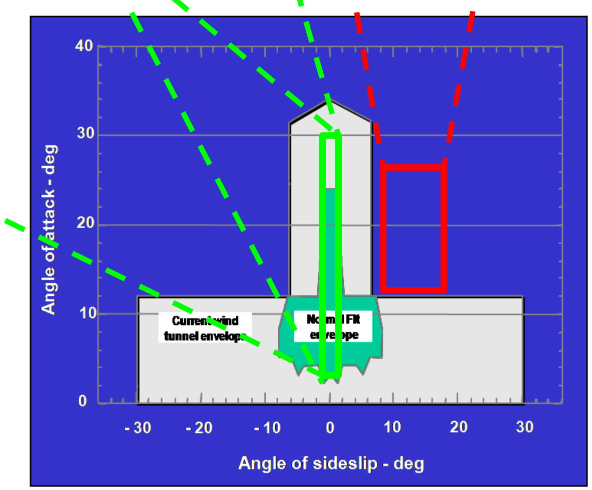
Baseline



AirSTAR :: Piloted Task (*AoA capture – high α*)





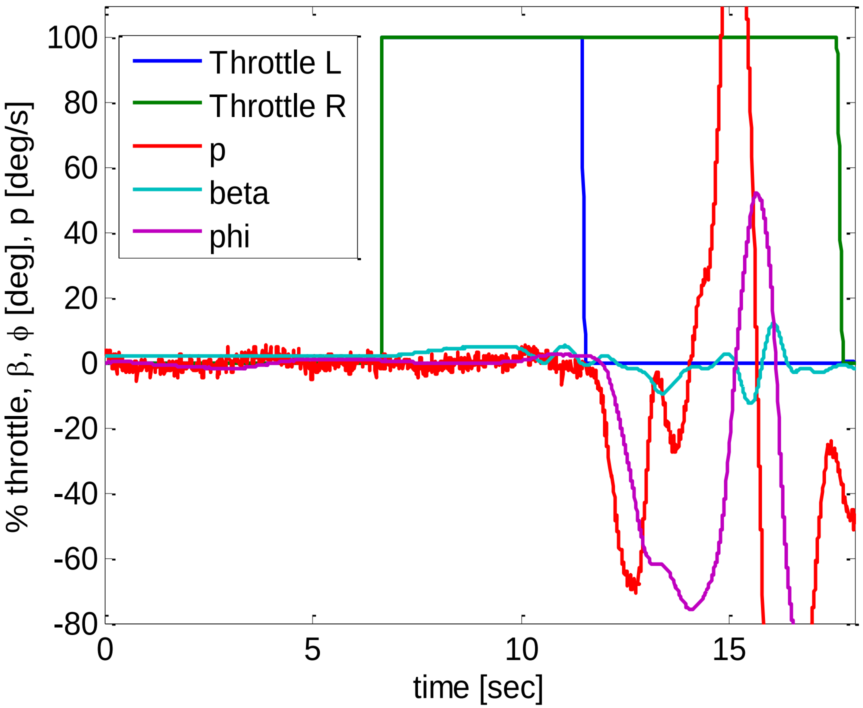


- α-β coupling for
  - L_1 adaptive controller at different AoA
  - L_1 adaptive vs. stick to surface control at 26 deg AoA

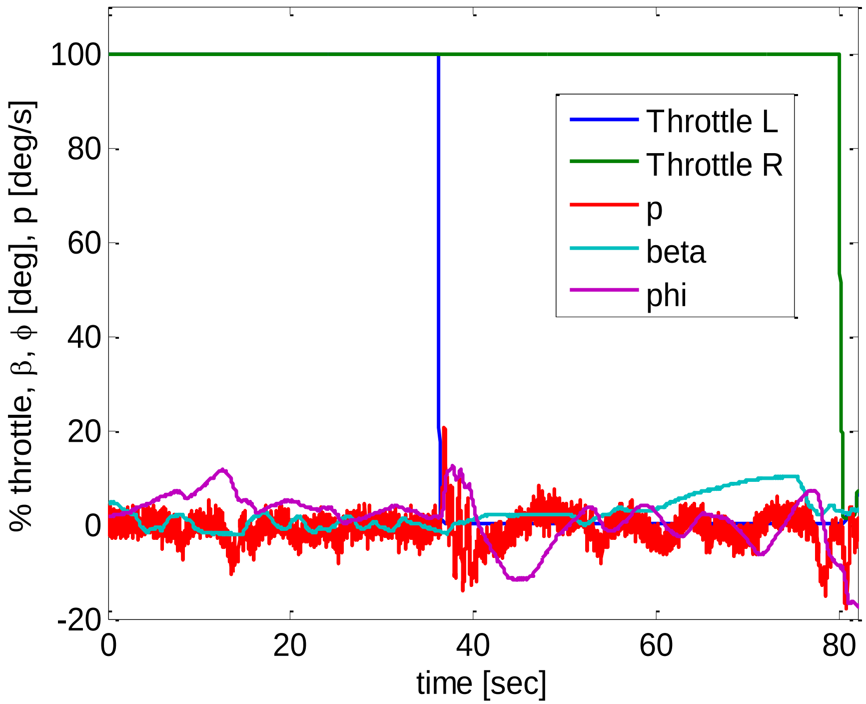
AirSTAR :: Piloted Task (*full throttle → asymmetric thrust*)

1. Full throttle (100%)
2. Climb at 25-30 deg pitch
3. Left Throttle cut to 0% in <0.5sec

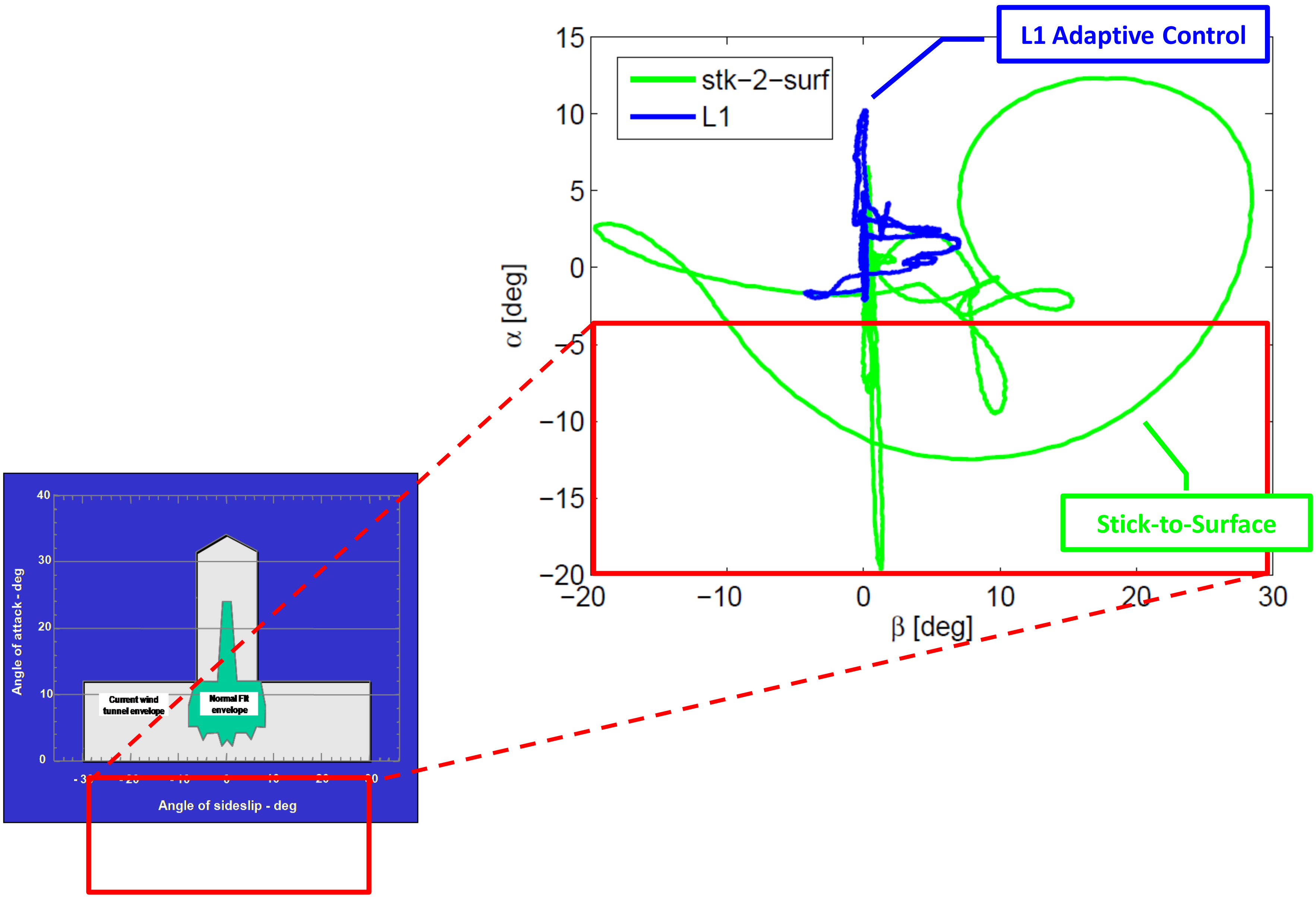
Stick-to-Surface



L_1 Controller



AirSTAR :: Piloted Task (*full throttle → asymmetric thrust*)



GTM T2 :: March 2010 Deployment

"…this is the first successful flight of an all-adaptive control law that deals with aircraft stability degradation as well as actuator failures…"

"…it is the first flight of a direct all-adaptive controller with a pilot in the loop…"

NASA RTD weekly key activities report

Dr. I. Gregory

Networked Control Systems

Challenges:

- Cyber challenges
- Modeling challenges
  - Need to predict the performance
  - Need robustness assessment

- Military use
  - Time-critical missions in constrained airspace
- Commercial use
  - Air-traffic control
  - Hospitals
  - Power grids, etc.

Networked Control Systems: Main Result

Consider the ideal system and the closed-loop real system. Assume that $f_i(t,x)$ is locally Lipschitz and $\frac{\partial f_i}{\partial t}$ and $\frac{\partial f_i}{\partial x}$ are linearly bounded in a compact set. Given arbitrary $\gamma \in \mathcal{R}^+$, if

$$\|G(s)\|_{\mathcal{L}_1}\alpha_{\max} + \frac{a}{\sqrt{\Gamma_{\min}}} + b\epsilon_{\max} < \gamma,$$

where $G(s) = H(s)B(I - C(s))$, $\Gamma_{\min} = \min_i \Gamma_i$, and $\epsilon_{\max} = \max_i \epsilon_i$, then

$$\begin{aligned} \|x - x^{\text{ideal}}\|_{\mathcal{L}_\infty} &< \gamma \\ \|u - u^{\text{ideal}}\|_{\mathcal{L}_\infty} &< \gamma_u. \end{aligned}$$

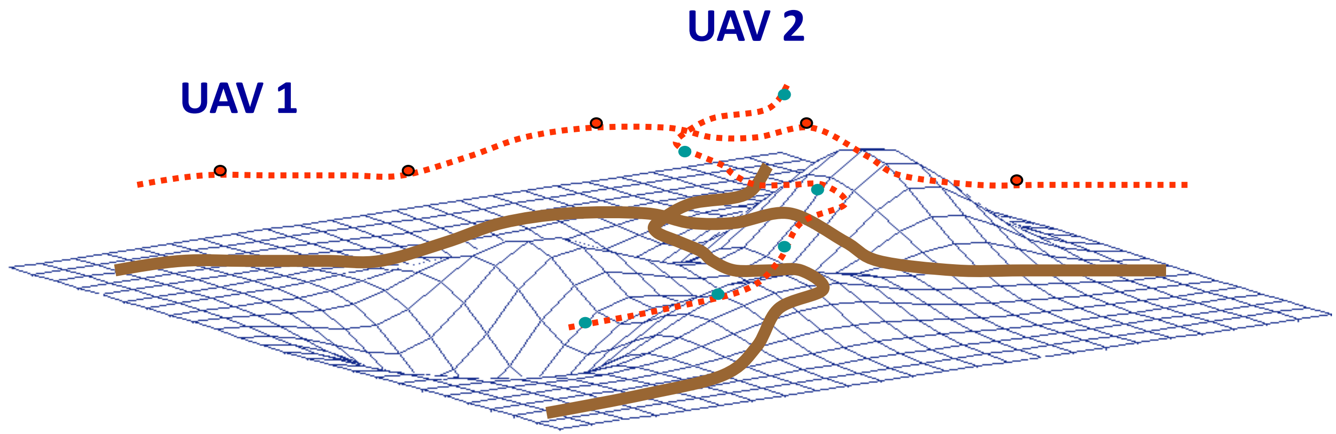
Moreover, the broadcast periods are always greater than a positive constant.

It suggests a tradeoff among the robustness, the adaptation, and communication.

X. Wang and N. Hovakimyan, IEEE Conference on Decision and Control, 2010 (Submitted)

Motivation in Applications of Homeland Security

- Time-critical applications for multiple UAVs with spatial constraints:
  - Sequential autolanding
  - Coordinated reconnaissance – synchronized high-resolution pictures
  - Coordinated road search



➢ Coordinate on the **arrival** of the leader subject to deconfliction, network, and spatial **constraints**

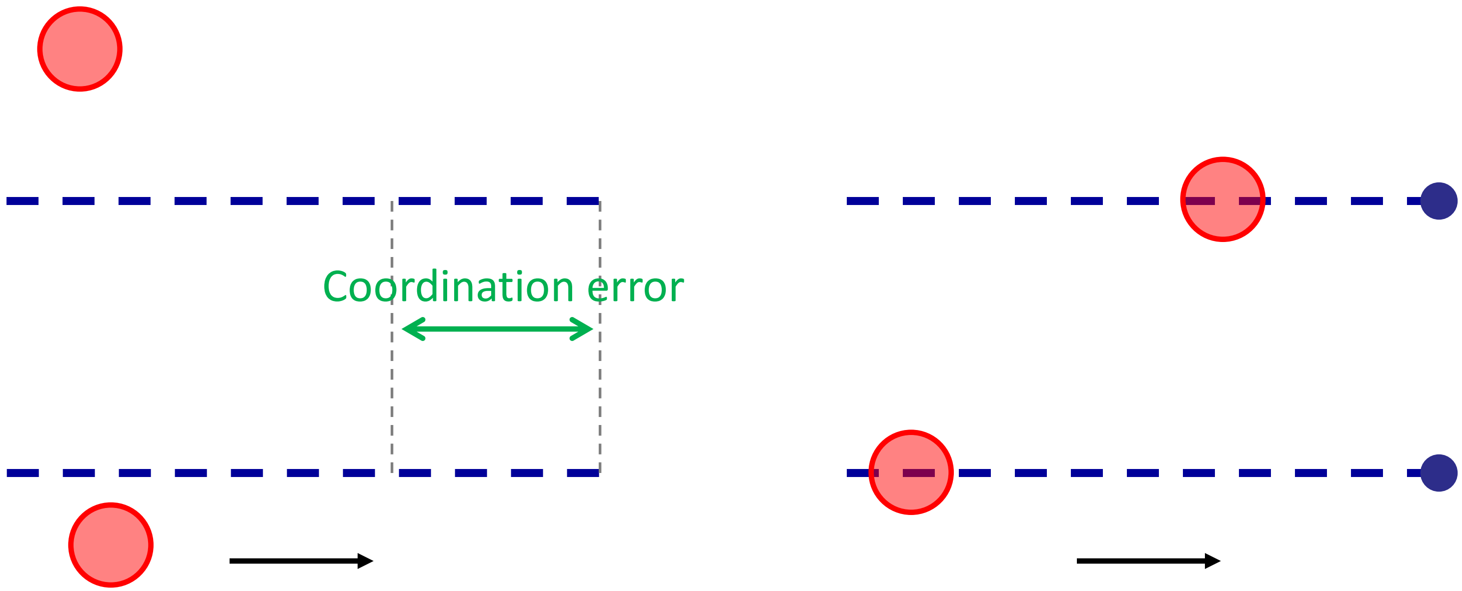
Overall Approach

- Integrated solution to **time-critical coordination problems** that includes:

1) **Real-time** (RT) **path generation** accounting for
   - ✓ Vehicle dynamics
   - ✓ Spatial and temporal constraints;
2) **Nonlinear path following** that relies on UAV **attitude** to follow the given path and leaving speed along the path as a degree of freedom;
3) **Time-critical coordination** adjusting the **speed** of each vehicle over a time-varying faulty network to provide robustness – account for the uncertainties and/or unavoidable deviations from the plan that cannot be addressed in the path generation step;
4) **L_1 adaptive control** to augment the off-the-shelf autopilots and improve path following performance and ensure coordination in time.

Key Idea

- **Decoupling of space and time:**
  - ✓ **In the path generation phase, reduces drastically the number of optimization parameters;**
  - ✓ **Makes the speed profile an extra-degree of freedom to be exploited in the time-coordination step.**



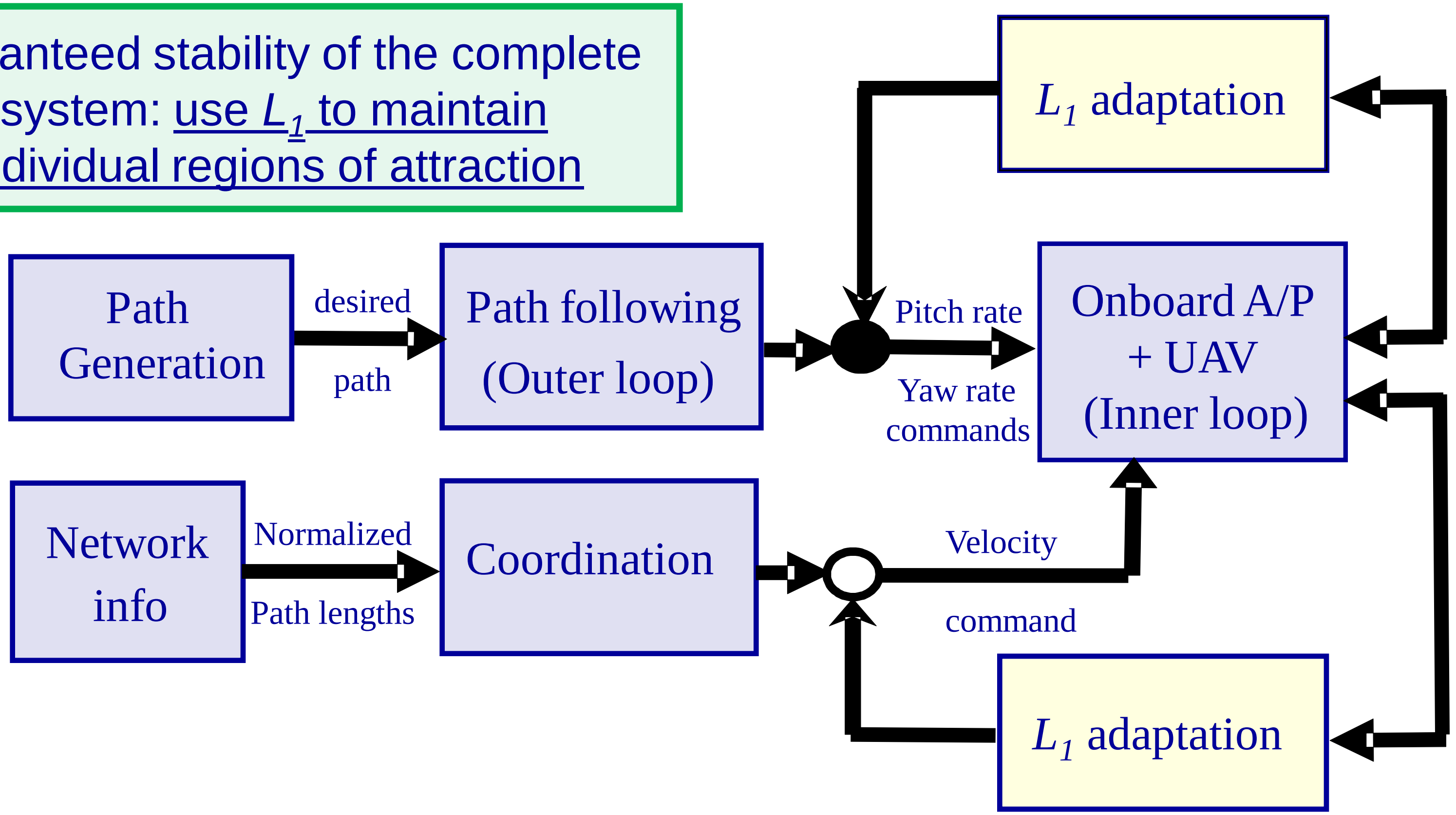
Each vehicle runs locally its own PATH FOLLOWING controller to steer itself to the path

Vehicles TALK each other and adjust their SPEEDS in order to COORDINATE themselves

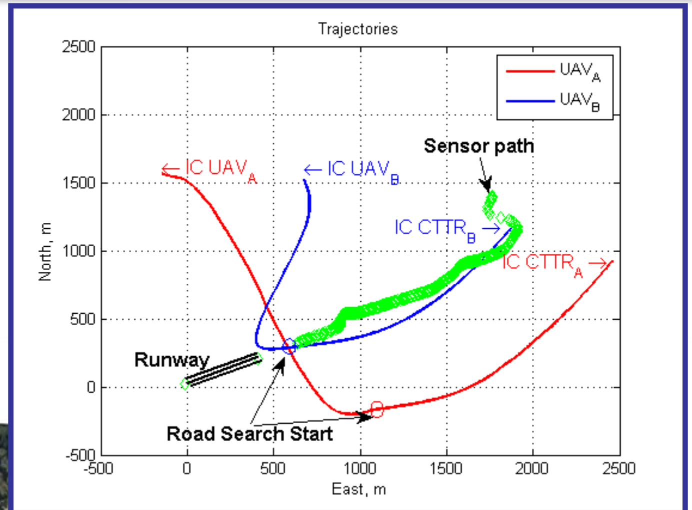
Architecture for Coordination with Limited Information

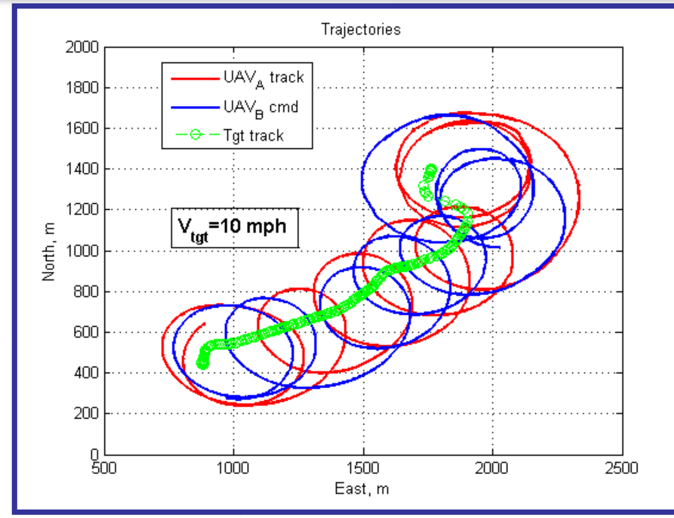
- **Objective:** successfully accomplish the missions given communication constraints from (wireless) network (limited bandwidth, package dropouts, time-delay, …)
- **Questions**: Lower bound on channel capacity for mission accomplishment? What are the effective communication schemes (coder, decoder)?
- The **solution** depends upon the **performance bounds** guaranteed by inner-loop controllers, the communication constraints and the given boundary conditions.

Guaranteed stability of the complete system: use L_1 to maintain individual regions of attraction

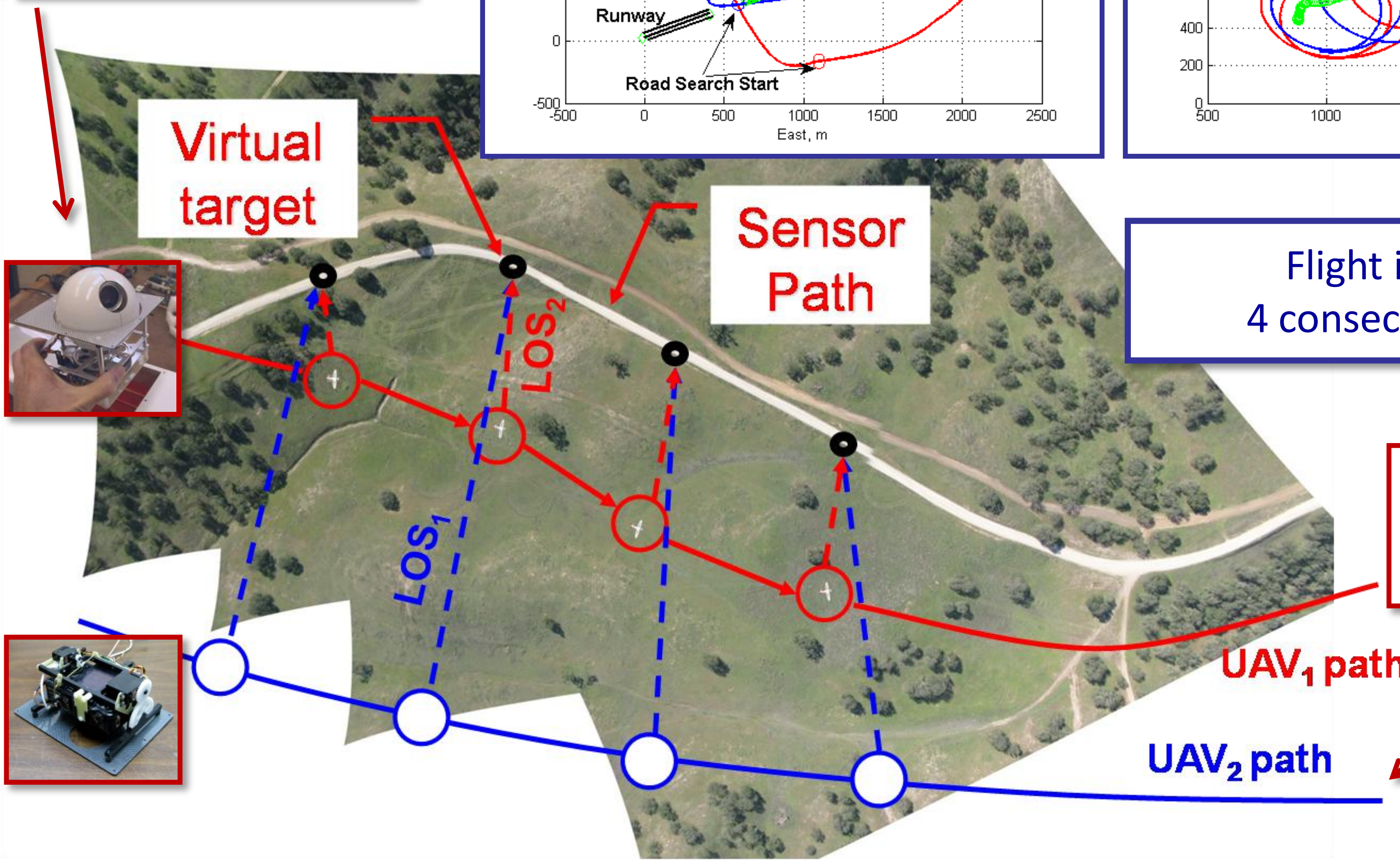


Flight Tests :: CPF - Coordinated Road Search





2DoF P/T gimbal with *video camera*



Flight imagery of 4 consecutive frames

Single DOF gimbal with *high resolution camera*

L_1 in Applications of Other Groups

- L_1 control of anesthesia (Carolyn Beck, UIUC)
- L_1 control of viruses (Tamer Basar, UIUC)
- L_1 control of smart materials with hysterisis (Ralph Smith, SUNC)
- L_1 control of drilling pressure (StatOilHydro, Norway)
- 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)
- L_1 control of helicopters (Carlos Silvestre, ISR, IST, Lisbon, Portugal)
- L_1 control of …..

Major Lesson Learned

Also in Adaptive Control…

… *robustness* has to be a part of the problem formulation,

and not just the "responsibility of analysis"

Conclusions

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

Performance limitations reduced to hardware limitations!

- Achieves clear **separation** between **adaptation** and **robustness**
  - 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…

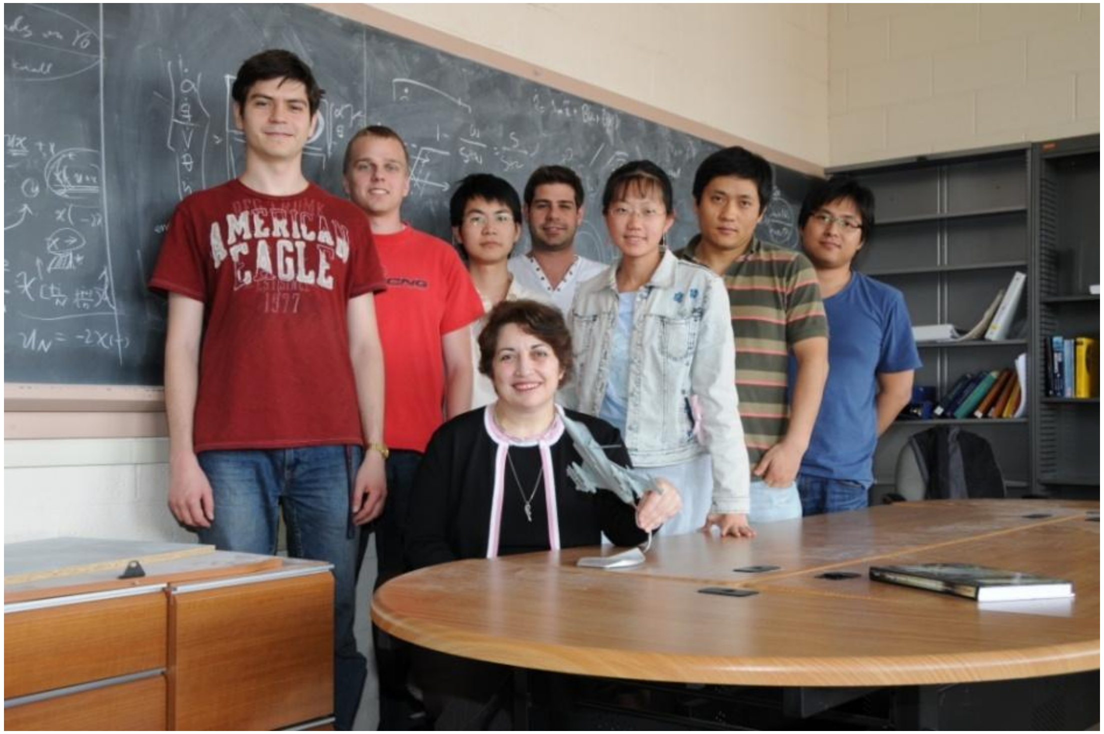
…at reduced costs!

with very short proofs!

Group, Collaborations, and Sponsors

Prof. Hovakimyan group:

- Chengyu Cao (University of Connecticut)
- Xiaofeng Wang (Post-doctoral Fellow)
- Ronald Choe (PhD student - AE)
- Evgeny Kharisov (PhD student - AE)
- Kwang-Ki Kim (PhD student - AE)
- Dapeng Li (PhD student - ME)
- Zhiyuan Li (PhD student - ME)
- Hui Sun (PhD student - ECE)
- Enric Xargay (PhD student - AE)



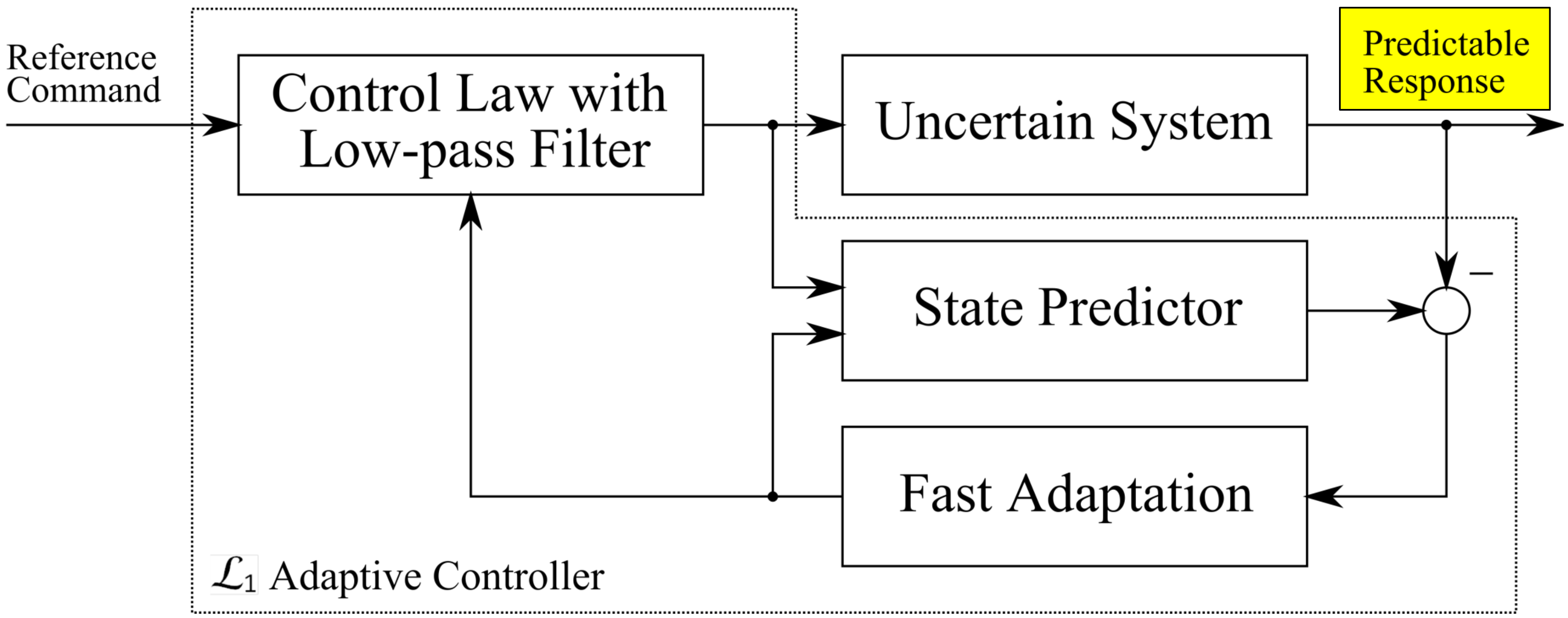
Collaborations:

- The Boeing Co. (E. Lavretsky, K. Wise)
- Wright Patterson AFRL (D. Doman, M. Bolender)
- WP AFRL CerTA FCS program/Boeing (T. Wendell)
- Raytheon Co. (R. Hindman, B. Ridgely)
- NASA LaRC and Ames (I. Gregory, N. Nguyen, K. Krishnakumar)
- NASA Dryden (J. Burken, B. Griffin)
- Eglin AFRL (J. Evers)

➢ Randy Beard (BYU), Isaac Kaminer (NPS), Jon How (MIT), Ralph Smith (NCSU)

Sponsors: AFOSR, AFRL (WP and EGLIN), ARO, ONR, Boeing, NASA

Architecture



Questions?