EuroGNC 2026 Keynote Address

Lockheed Martin Aero, Skunk Works

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Discussion Topics

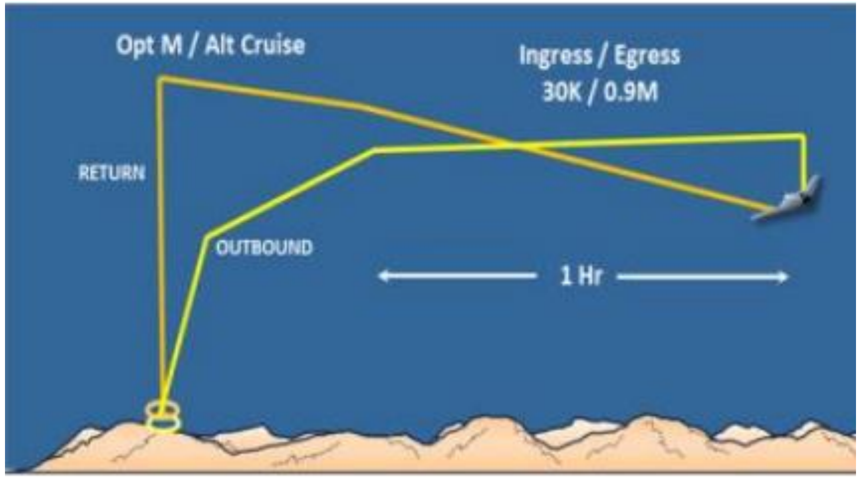
- **Collaborative Research & Development**
- NATO-affiliated R&D Groups
  - AVT-424; Active Flow Control (AFC)
  - AVT-419; Control Allocation Evaluation/Demo
- NASA University Leadership Initiative (ULI)
  - Consultants to University of Illinois Urbana-Champaign (UIUC)
- TU Delft, Czech TU, IIT, Others

- **Internal Research & Development**
- L1 Robust Control
  - Implementation as a bolt-on subsystem
  - Demonstrated in piloted dome simulation
  - Flight test evaluation

Active engagement in control-related research & development

Recent History of NATO Active Flow Control Research & Development

- Started in 2013 with Specialists Meeting on Active Flow Control
  - Methods included Coanda jets, slot blowing, and sweeping jets
- AVT-239 planning year in 2014, project ran 2015-2018
  - Focus on ingress/egress mission segments related to the Innovative Control Effectors (ICE) aircraft platform
  - https://www.youtube.com/watch?v=uPvJi0s-4A0
  - Results documented in special sessions at AIAA SciTech 2019
- AVT-350 planning year in 2020, project ran 2021-2024
  - Focused on takeoff and landing mission segments
  - Continued subsystem integration and maturation
  - Results documented in special sessions at AIAA SciTech 2025
- AVT-424 planning year in 2025
  - Performing wind tunnel tests, CFD
  - Continuing integration, maturation, and aerodynamic refinement



Representative ICE Mission

ICE Model Aircraft

Graphics approved for public release under AER2024090744

Active flow control refinement and maturation continues

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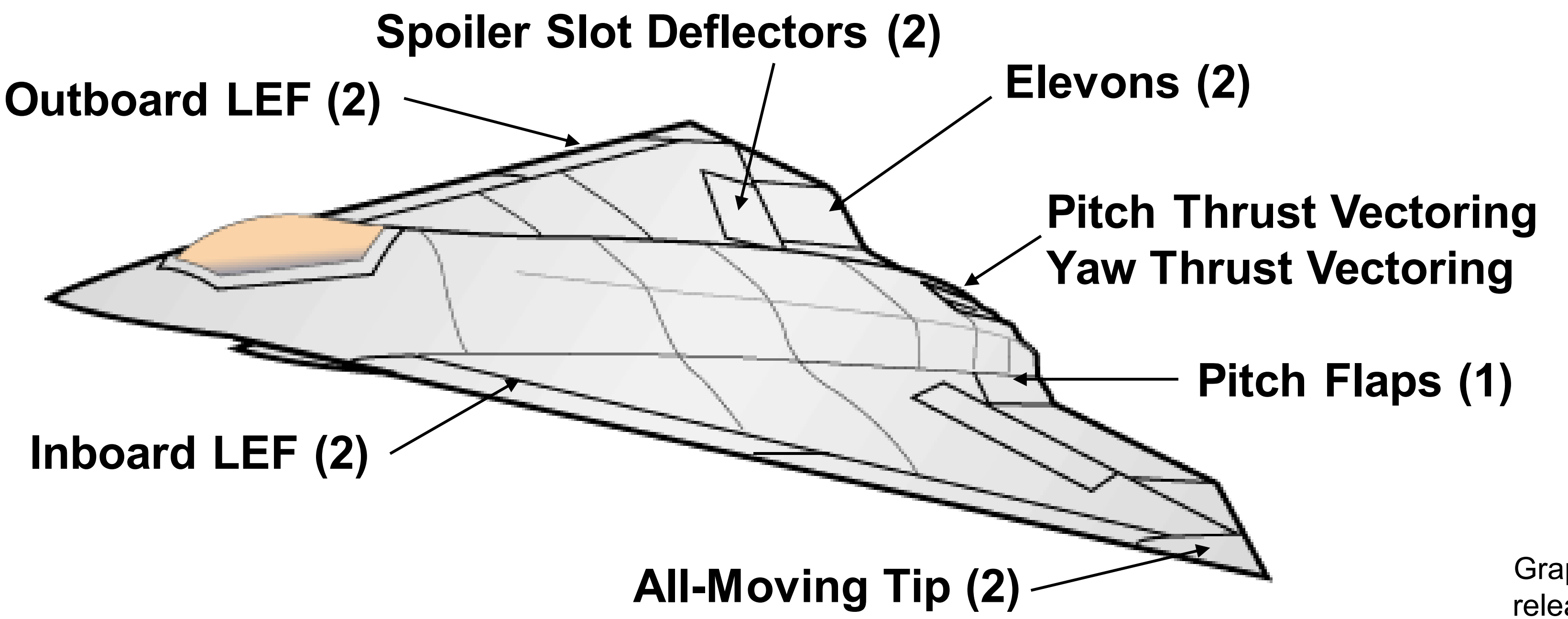
ICE Baseline Control Effector Suite

Simulation model contains aerodynamic coefficients and thrust vectoring
Available in MATLAB/Simulink format

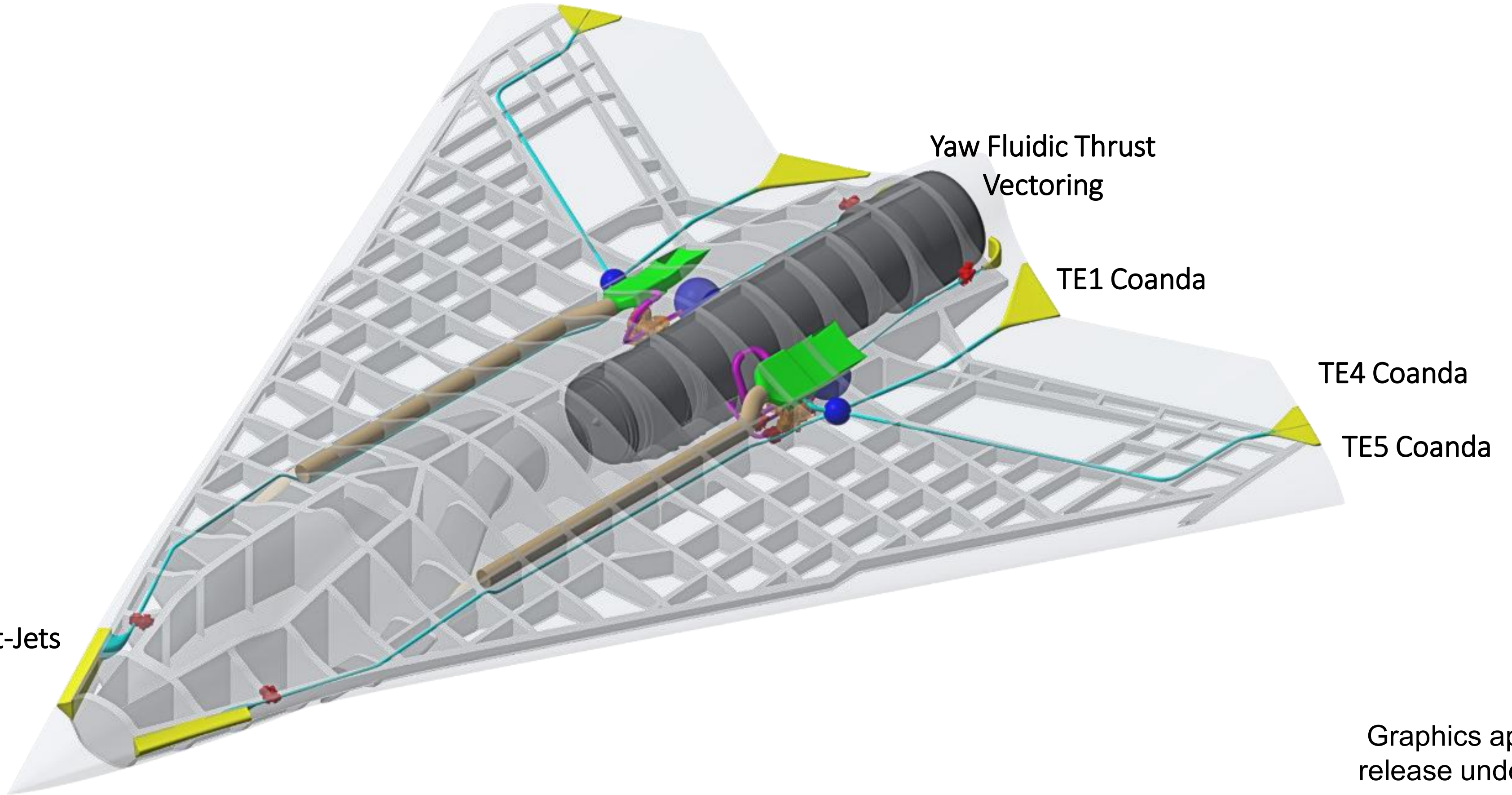


Graphics approved for public release under AER201612015

Model publicly released to foster collaboration and control system technology development

ICE Active Flow Control Effector Suite

Simulation model updated to include aerodynamic increments due to active flow control



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Active flow control increments added to supplement traditional effector suite

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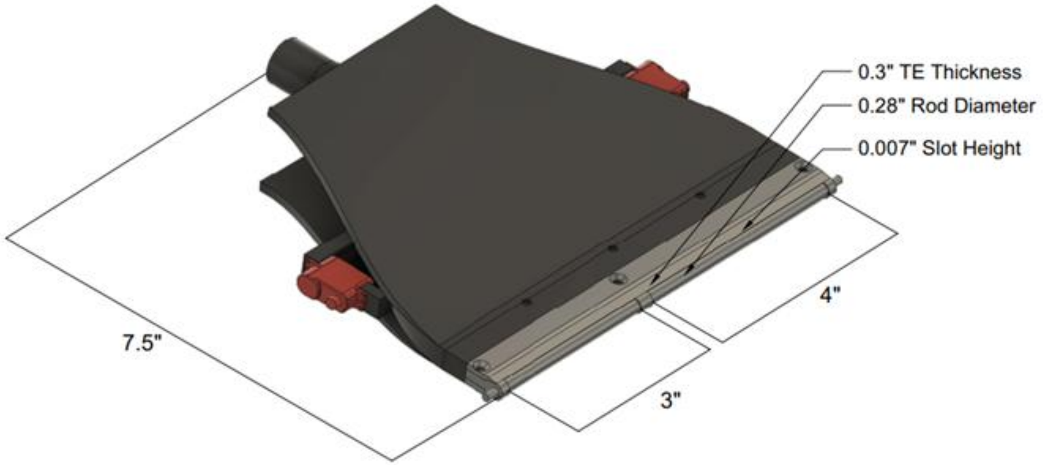
Example: Active Flow Control Effector Authority on a Subscale RPV

<u>Split Coanda Control Effectors</u>

- Circulation control around the airfoil is achieved by utilizing the Coanda Effect
  - Pressurized plenum and specially designed trailing edge to induce Coanda Effect
- Direction of Coanda jet is adjusted by a rotating servo-controlled cam at the plenum exit.
  - Coanda jet angle varies +/-135 deg without an external flow
  - Bandwidth is limited by the servo to ~ 6 Hz (k = 0.74)
- Split design allows for a variety of control types
  - IB/OB independent (usually IB-elevator, OB-aileron)
  - IB/OB together (single 7-inch Coanda jet)
  - Clamshell:
    - config 1 - IB down/OB up
    - config 2 - IB up/OB down



Information and photo/video courtesy of Dr. David Williams, IIT, Presented at AIAA SciTech 2025

Coanda effectors act as traditional trailing edge elevons or ailerons

AVT-424: Mission Led Design of Air Vehicles with Active Flow Control

Objective

Continued assessment and maturation of AFC on next-generation tailless UAS

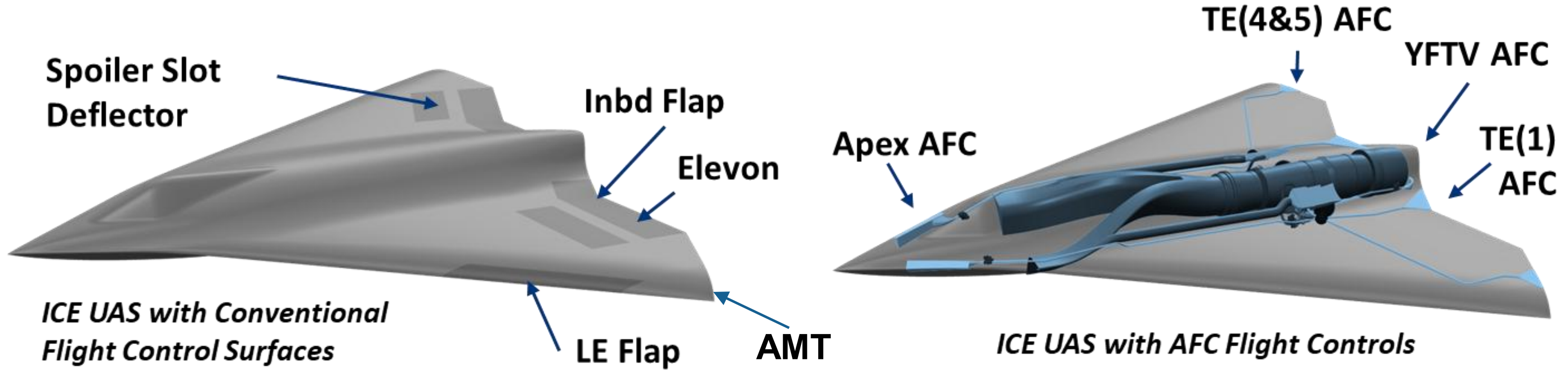
Scientific Topics

Refinement of mission benefits of AFC (ingress/egress, take-off/landing, manoeuvring, etc.)

Improve understanding of safety, reliability of AFC

Start: January 2025 (planning year)

Report: Special sessions at AIAA SciTech 2029



ICE UAS with Conventional Flight Control Surfaces

ICE UAS with AFC Flight Controls

Graphics approved for public release under AER2024090744

Foster transition of active flow control to a NATO country platform

AVT-419: Demonstration of Novel Control Allocation Methods

Objectives

1) Increase the TRL of novel control allocation techniques by assessment against key criteria
2) Develop capability that allows rapid and low-cost assessment of those control techniques

Topics

- Integration of novel controls to optimize specific control tasks
- Optimization of control allocation objectives/solutions depending on vehicle mode
- Optimization of control allocation solutions to improve vehicle performance or maneuverability / survivability
- Fault detection and re-allocation of control effectors to mitigate fault

Deliverables

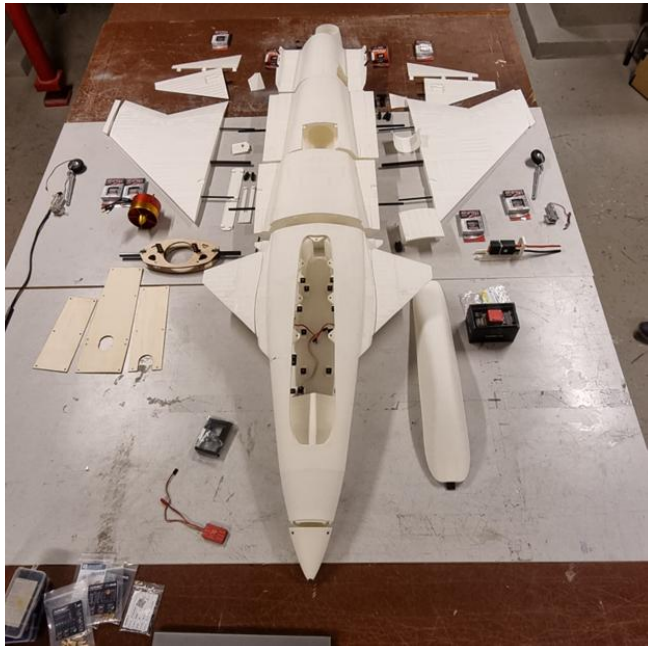
- Enhanced proceedings document providing a concise summary of activity
- Strategic direction for future follow-on activity

Start: January 2025 (planning year)
Report: Special sessions at AIAA SciTech 2029

Explore and evaluate various forms of control allocation in flight experiments

AVT-419 Progress Update

- Agreed key areas of interest within community
  - Centralized and decentralized control allocation strategies
  - **Artificial intelligence and machine learning in control allocation**
  - **Implementation and certification**
  - **Objective based control allocation (e.g., quadratic programming)**
  - Control allocation with novel effectors
  - **Fault tolerant control allocation**
  - Hardware considerations on control allocation
- Build and fly a subscale demonstrator
  - Modelling and simulation
  - Hardware element - Rapid prototype subscale demonstrator
  - Software element - Understand methods of implementation, consider certification approaches



Photos courtesy of Roger Larson, Saab AB.

Flight experiment details being worked at the spring, 2026 meeting

Play it SAFE: Winning the Race Against Cost and Schedule

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Dr. James Ramsey, Lockheed Martin Fellow
Dr. Aaron McKinnis, Lockheed Martin ADP

Approved for public release in AER2026021256

Overview

- Strategic Importance
- Technology Overview
  - $\mathcal{L}_1$ Robust Control Law
  - Bolt-On SAFE
- Flight Test Results
- Continued Development
  - Single- and Multi-Threaded Attractive Manifold (S-TAM/M-TAM)
- Conclusion

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Strategic Importance

- As customers push for cheaper systems at speeds previously unheard of, aerospace companies are investing heavily in tools and processes
    - Digital twin architectures
    - Streamlined parts acquisition
    - AI workflow integration
- While great for overarching programmatics, most new tools fail to address the key to success: **physics**
- Two large drivers of a new air vehicle's cost and schedule are:
    - Wind Tunnel Testing
    - Flight Testing/Envelope Expansion

Understanding the physics of a new system is expensive and time-consuming

What is SAFE?

It is an acronym for **S**mart **A**daptive **F**light Control **E**nvironment

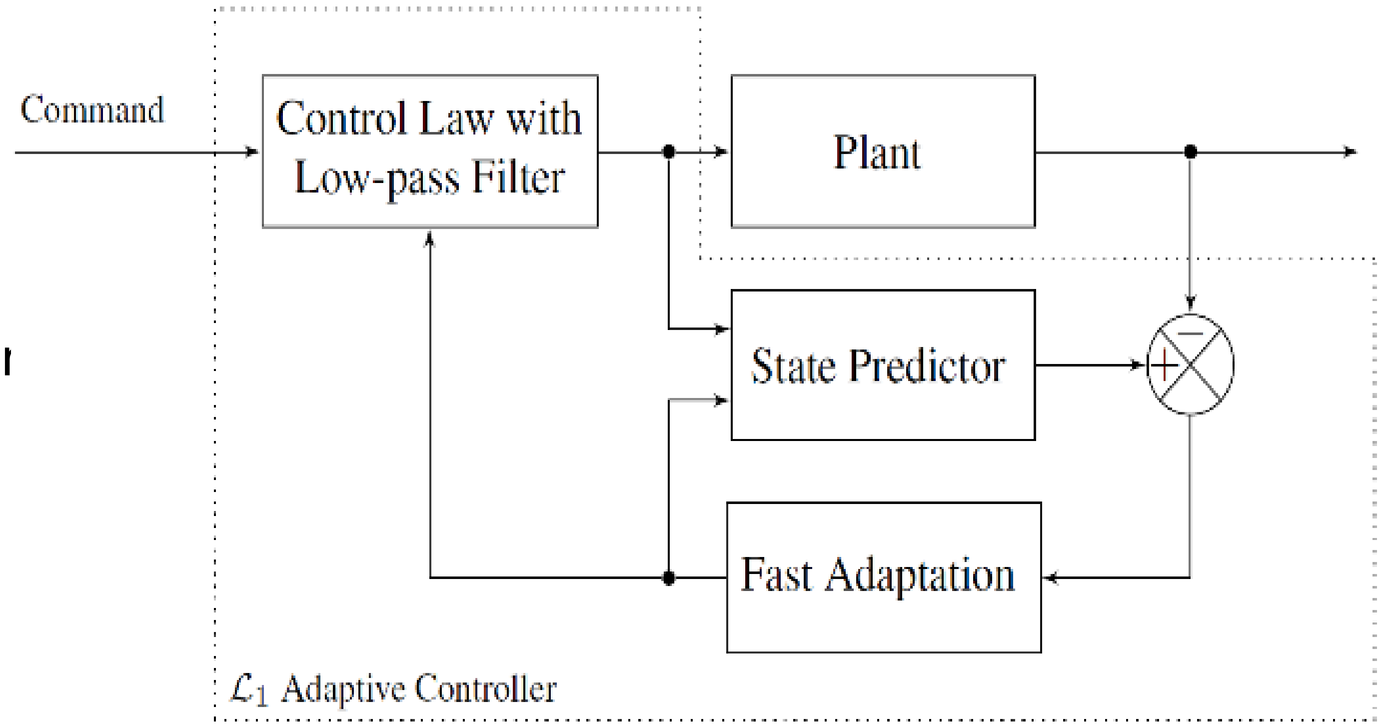
It is a collection of robust and adaptive control techniques that:

- "Bolt On" to existing control techniques with no modification to original controllers/tunings
- Grant increased robustness to unmodeled dynamics and non-linearities
- Allow pathways for both on and offline learning of underlying physics

Results: Shortened time to flight test with reduced physics modeling

$\mathcal{L}_1$ Modified Piecewise Constant (MPwC) Control

- Developed by Hovakimyan and Cao[1]
- Control technique relies on a state predictor and a fast adaptation feedback
- Low-pass filtering of the control law signal decouples the adaptation from the control
- Piecewise constant implementation has been modified with an additional integration path
- Supports classical linear analysis

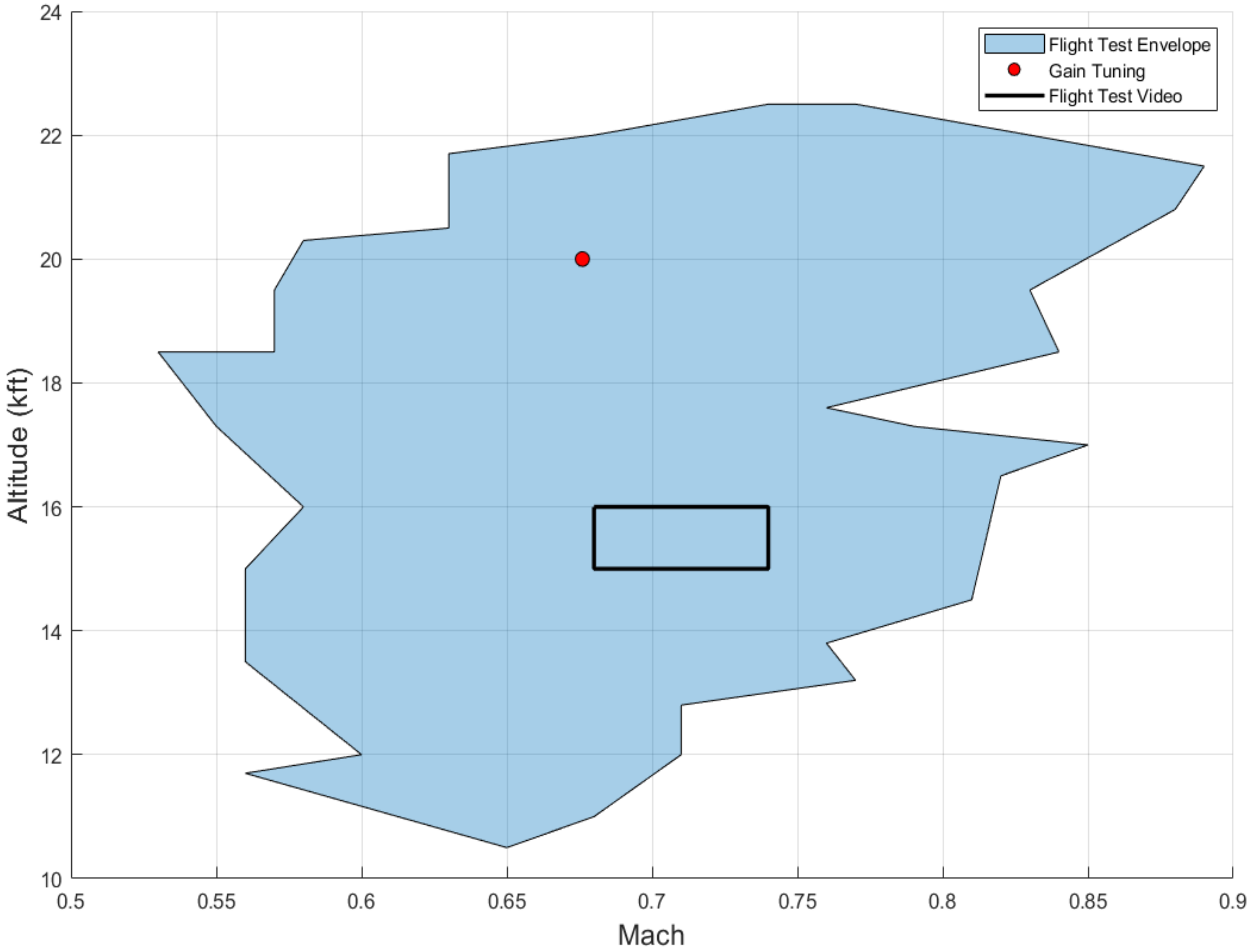


$\mathcal{L}_1$ MPwC chosen as the core of the SAFE algorithm due to exceptional robustness

[1] Hovakimyan, Naira, and Chengyu Cao. *$\mathcal{L}1$ adaptive control theory: Guaranteed robustness with fast adaptation*. Society for Industrial and Applied Mathematics, 2010.

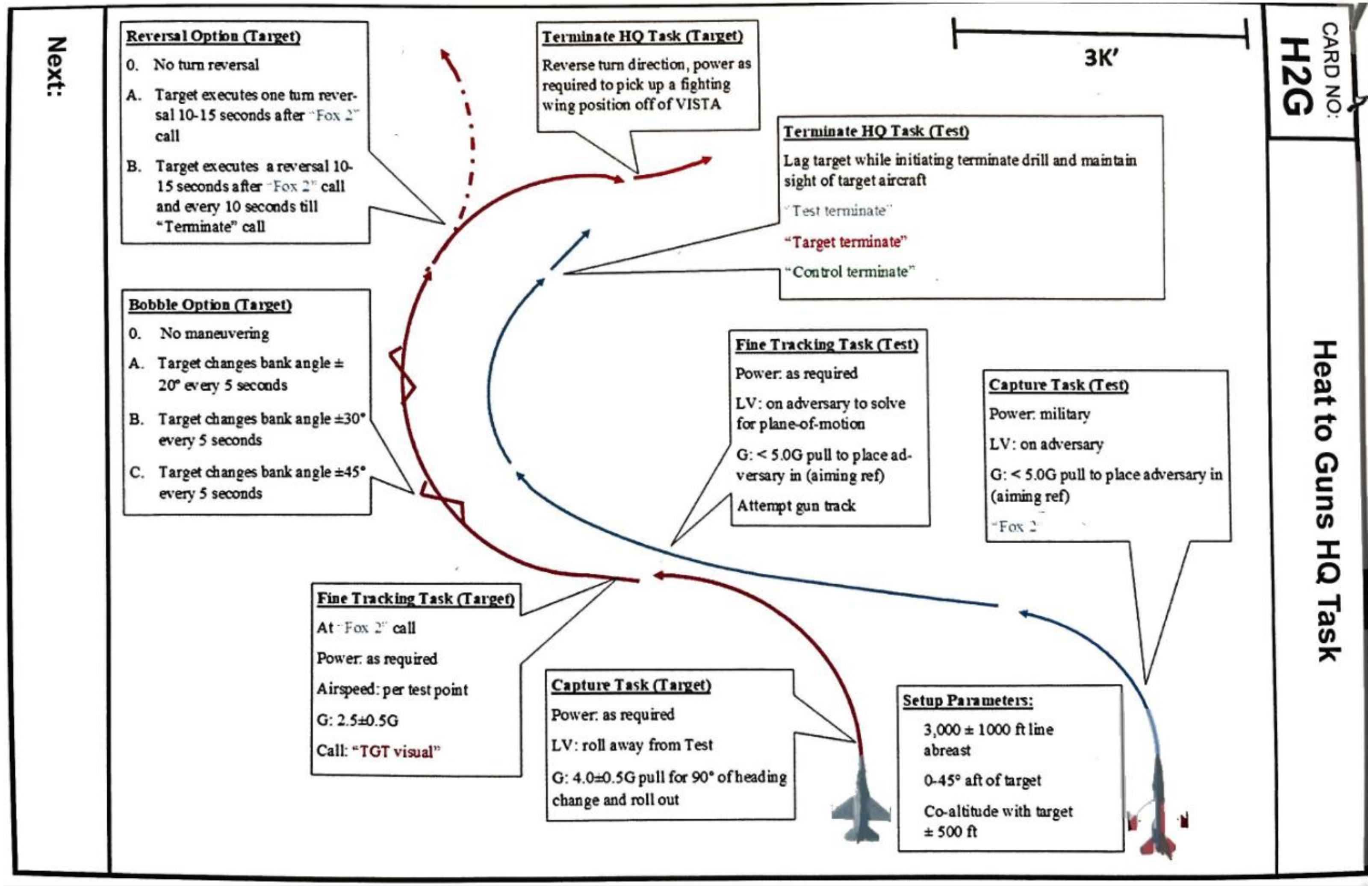
Flight Testing Setup

- System hand-tuned pre-flight using a single condition across desktop, pilot-in-the-loop, and HIL simulators
- Flight tests conducted with the USAF Test Pilot School (TPS) on the X-62A VISTA aircraft over a two-week window
  - Traditional Parameter Identification (PID) maneuvers graduating to stressing acquisition and tracking tasks
  - Introduced effector lock, effector degradation, and OBM mismatches to probe nonlinear disturbance rejection
  - Double blind flight testing with SAFE On/Off to compare with designed NDI controller



A single tuned condition slashes engineering hours, SAFE delivers full-envelope control

Heat to Guns (H2G) - Task Description



Starting from a given separation distance, VISTA aircraft will attempt to acquire and track the T38 while in an ~3G windup turn

H2G provides a representative high-level task for controller testing

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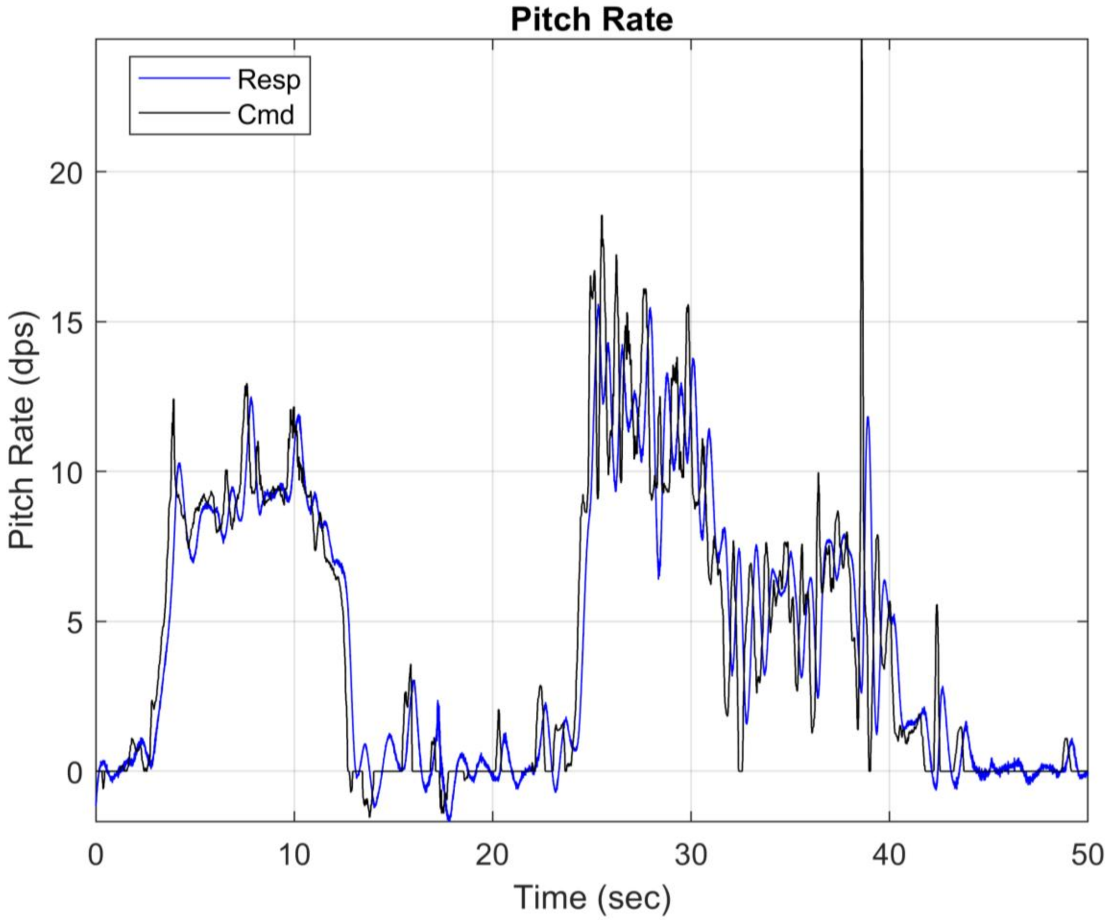
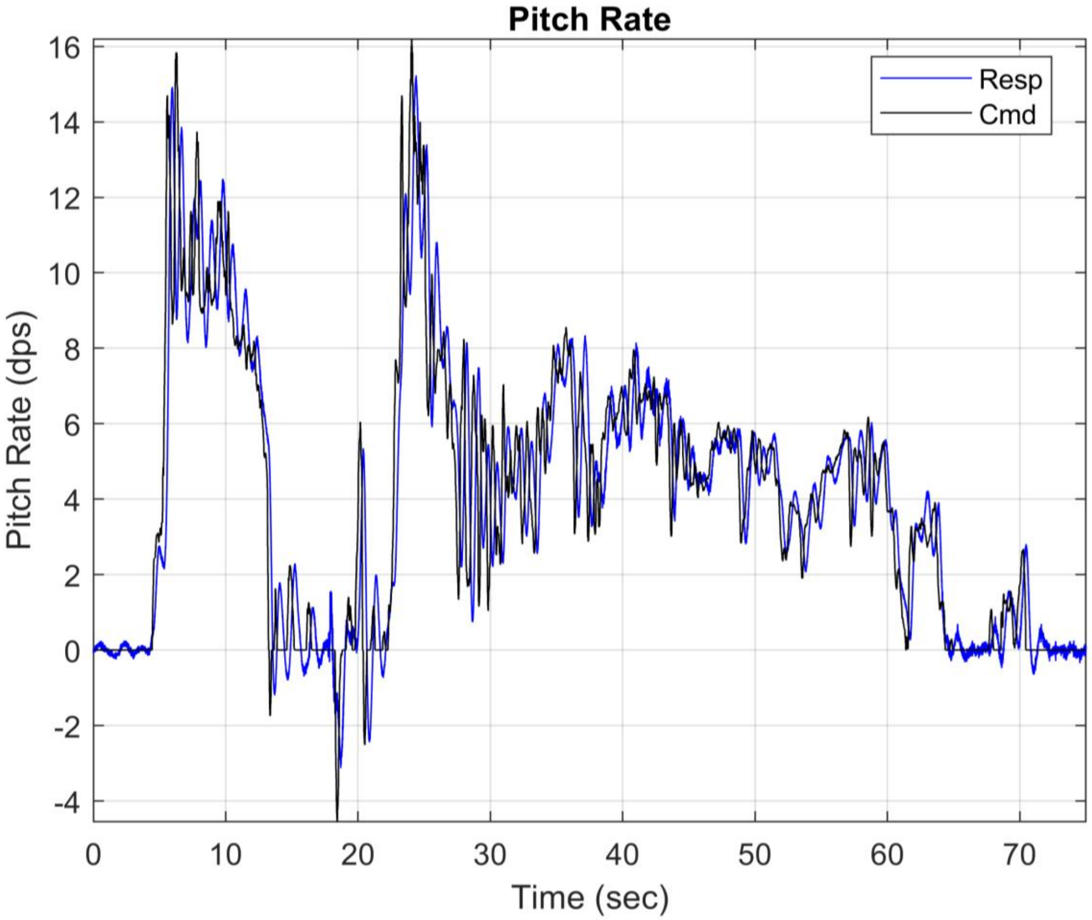
Heat to Guns – Base (i.e., no failures/mismatches)



SAFE Off



SAFE On

Little correction needed by L1 over baseline NDI

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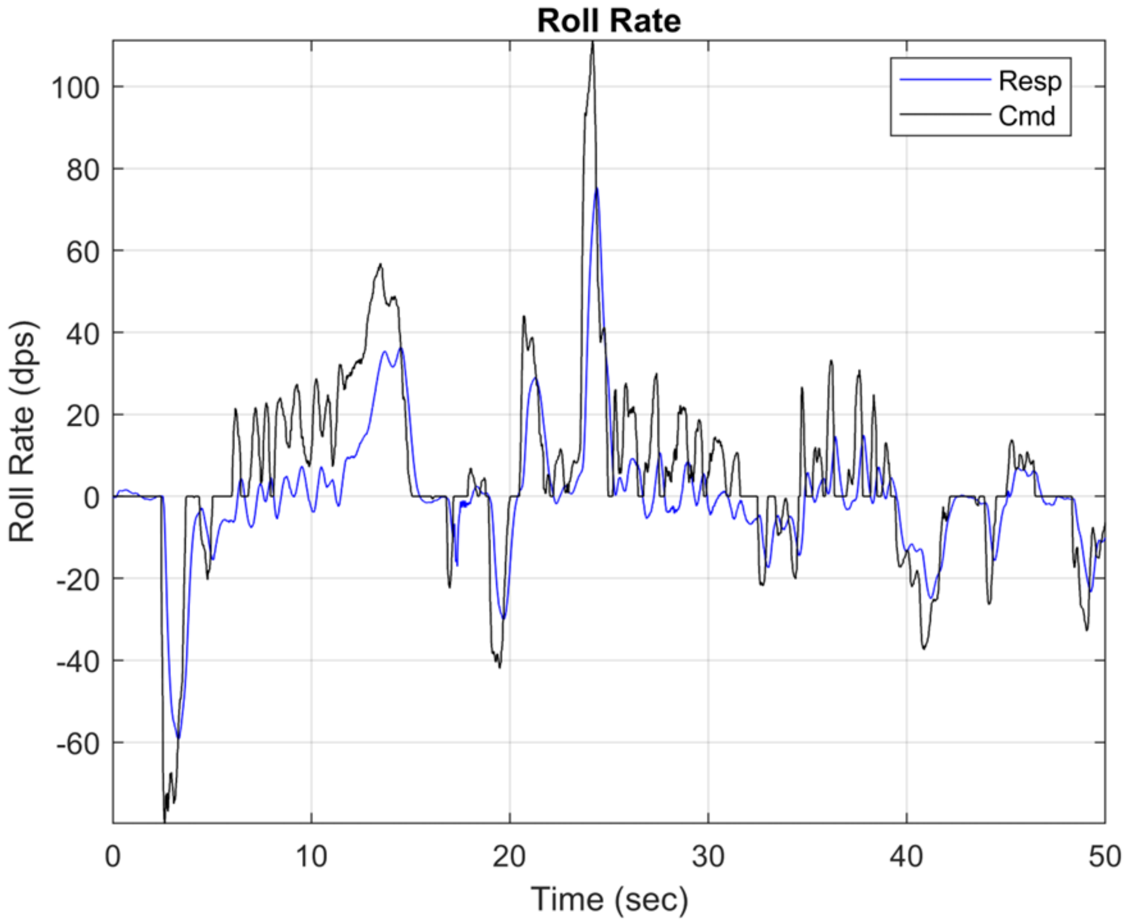
Heat to Guns – Base (i.e., no failures/mismatches)



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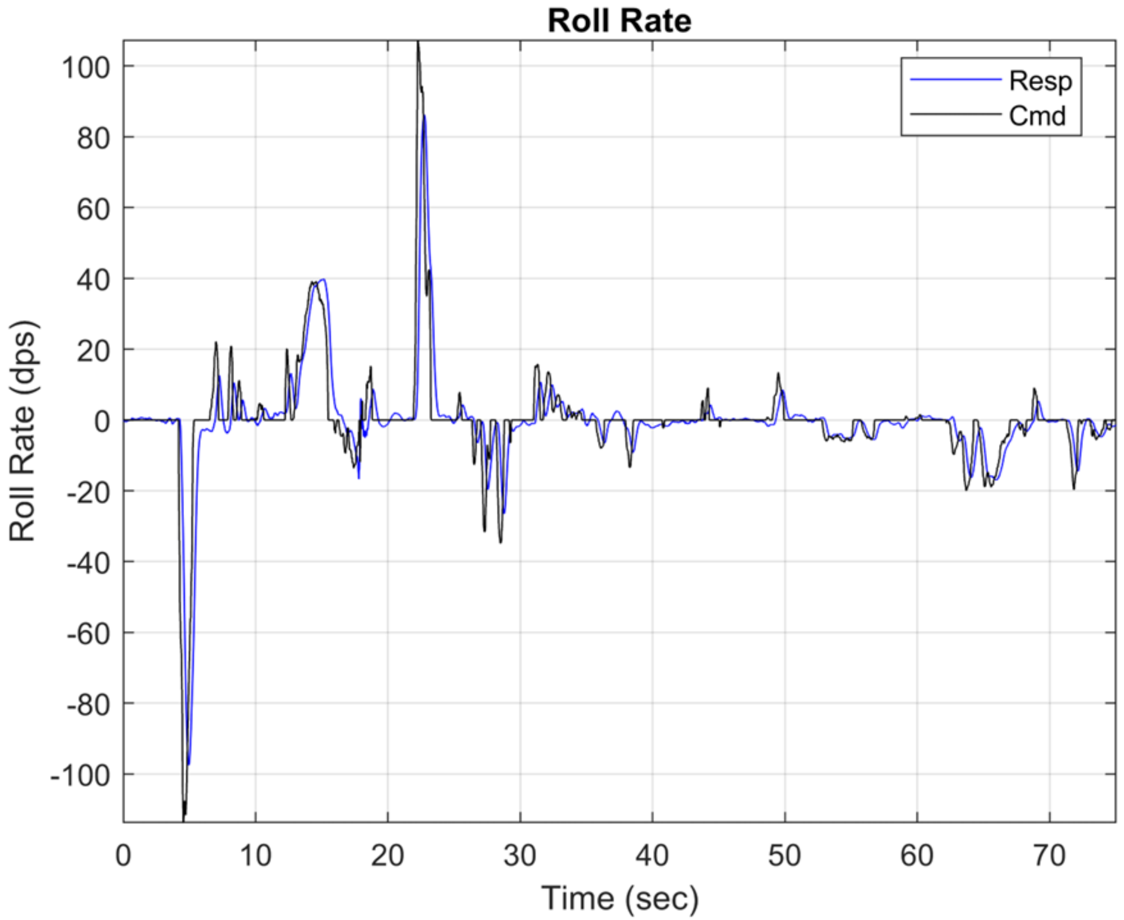
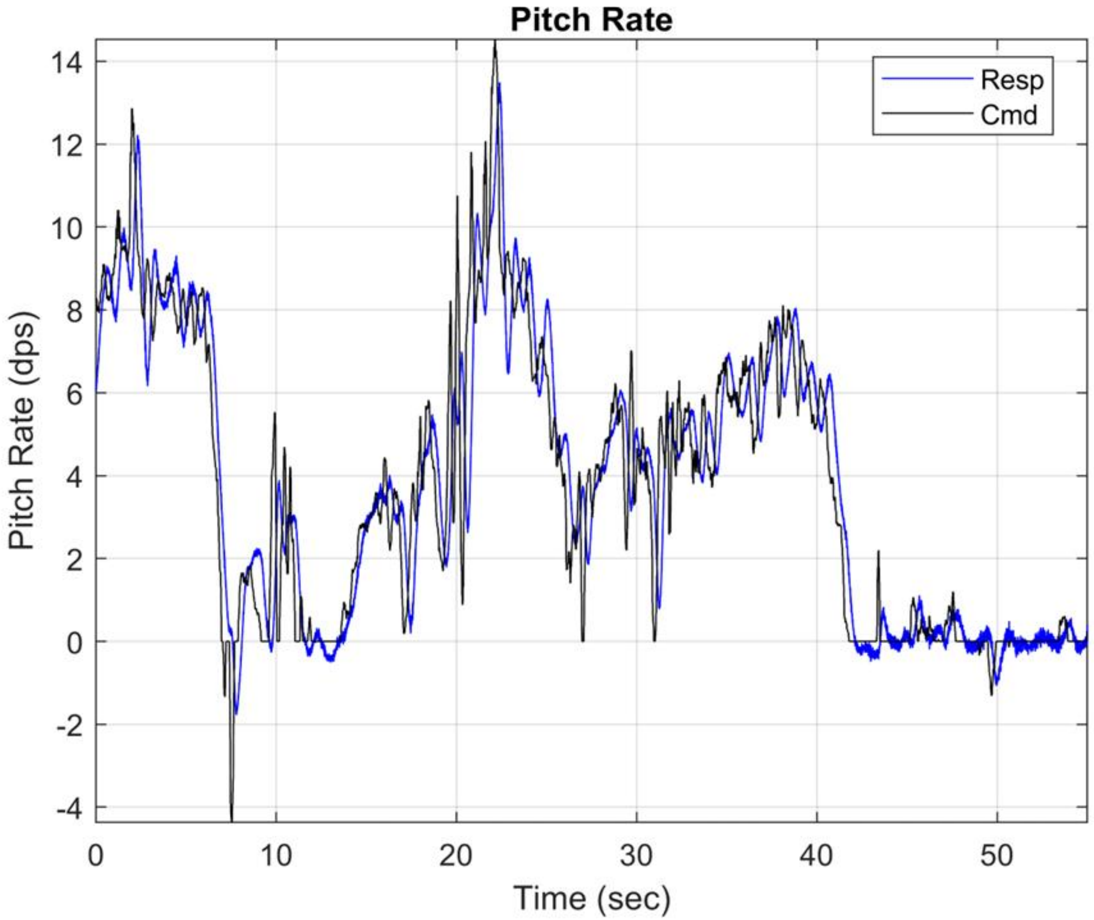


SAFE On

Mild corrections generated by L1 for normal operations

Heat to Guns- Failed Right Flap



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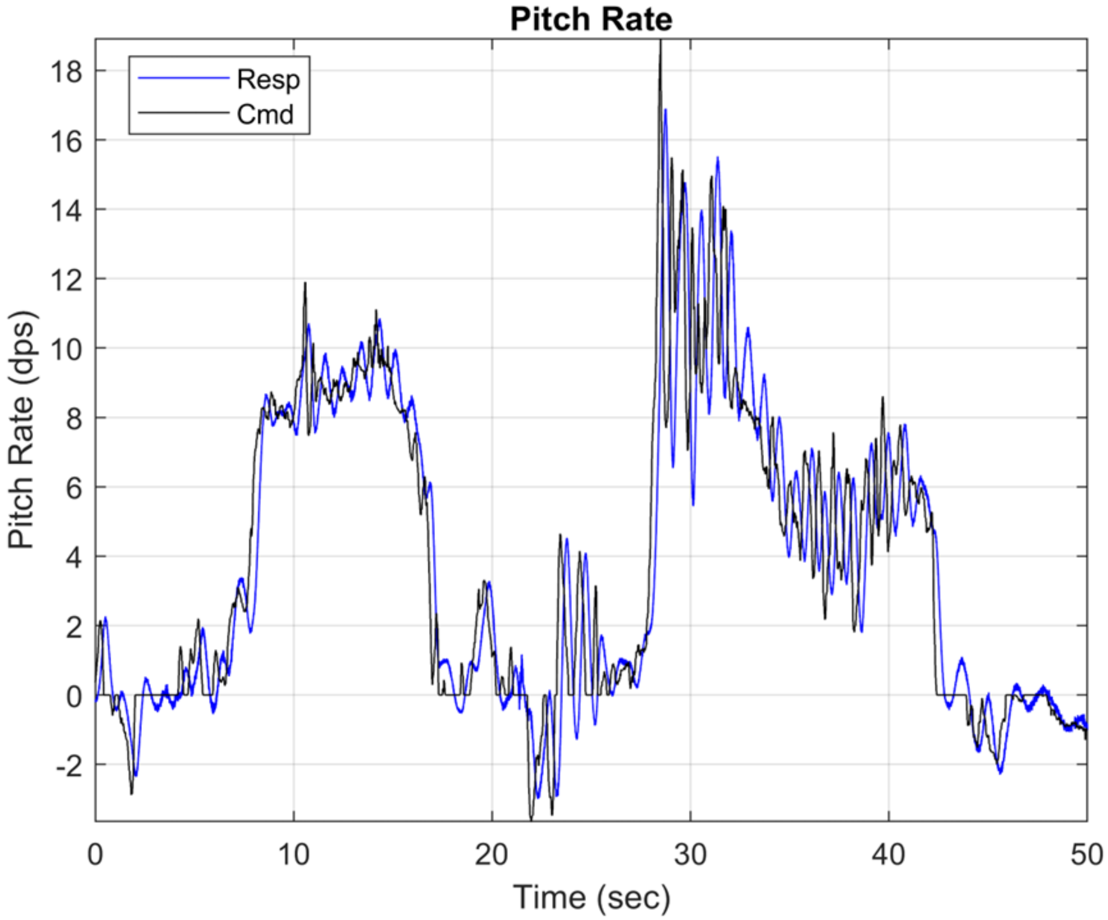

SAFE On

Comparable tracking in the pitch axis with or without SAFE

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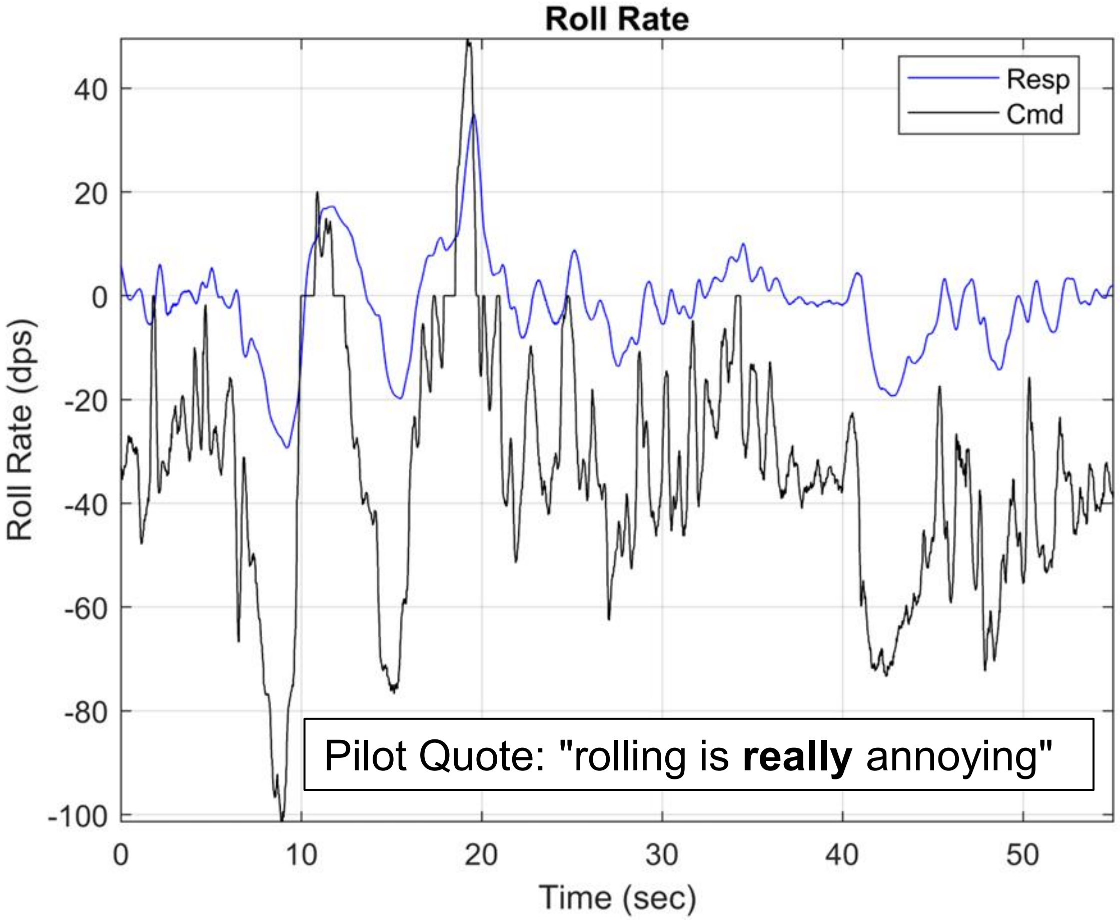
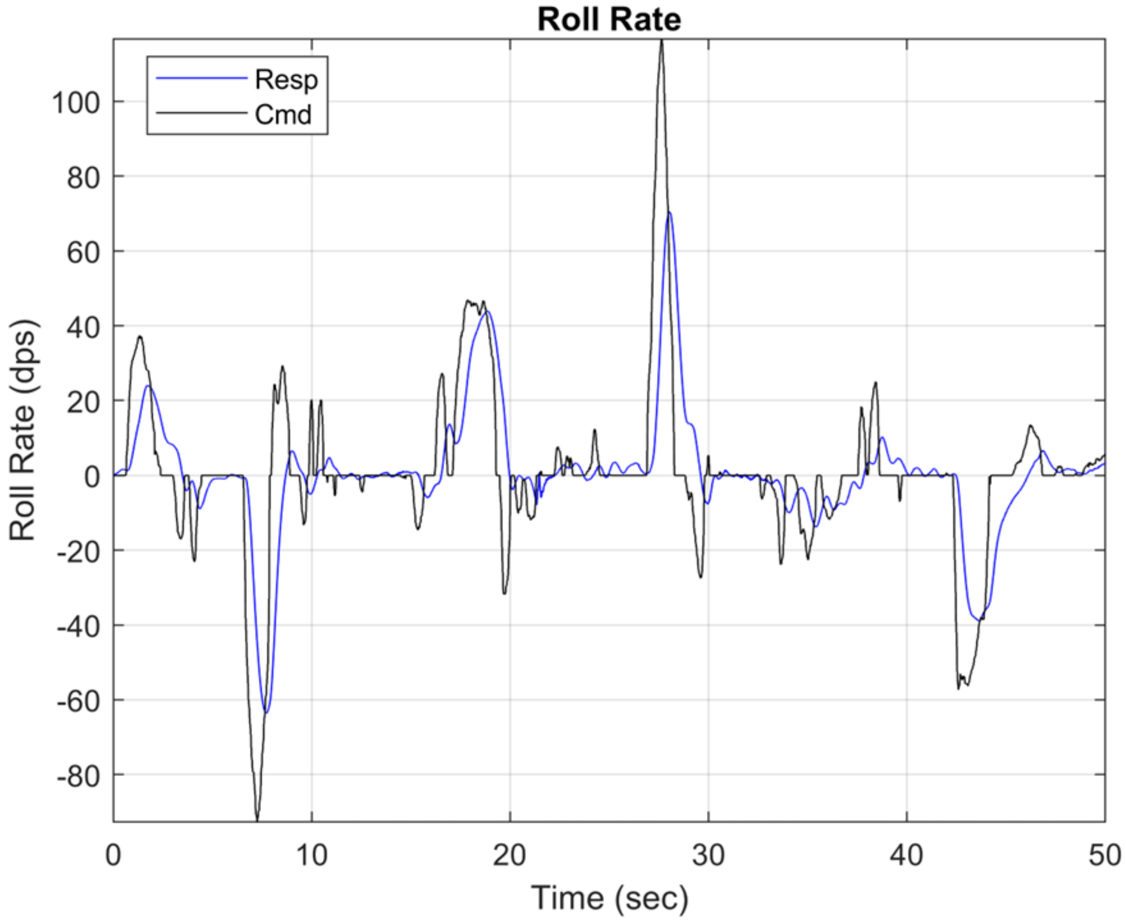
Heat to Guns - Failed Right Flap



SAFE Off



SAFE On

Bias corrected; less pilot input required with SAFE On in roll axis and improved tracking

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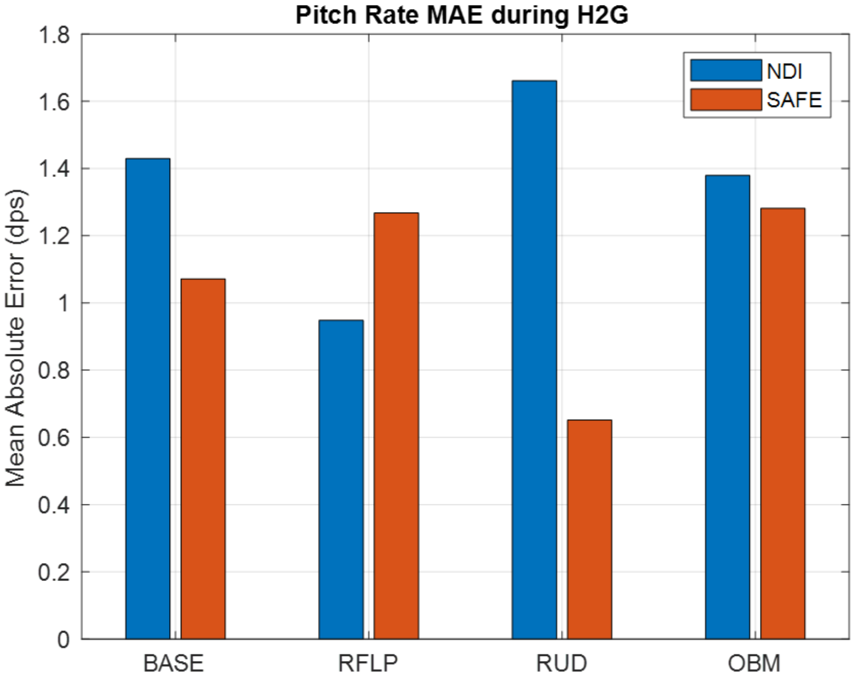
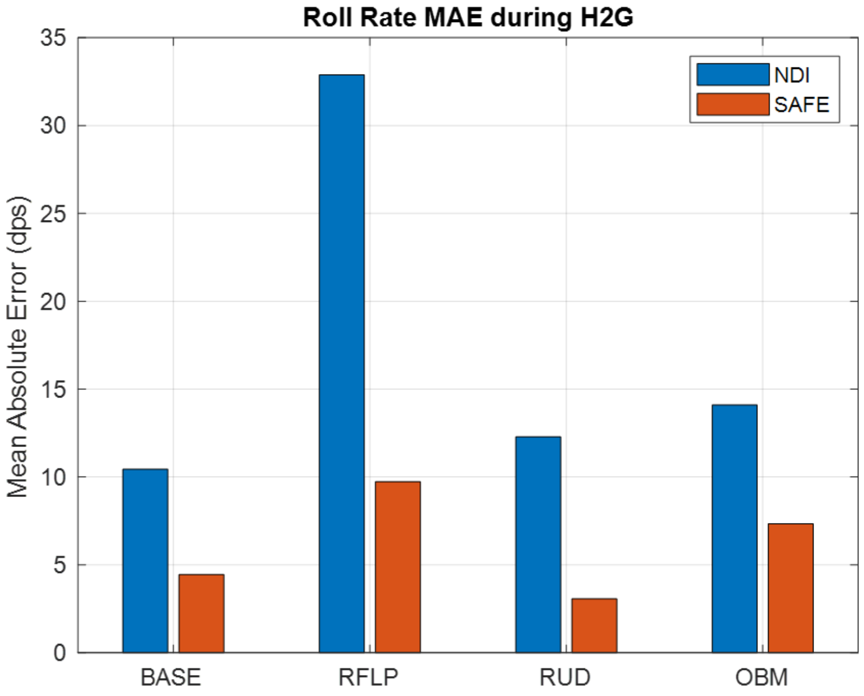
Heat To Guns Mean Absolute Error





SAFE showed increased robustness and tracking performance across all four of the tested scenarios

SAFE consistently outperforms the baseline controller

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Flight Test Video

https://www.facebook.com/lockheedmartin/videos/our-skunk-works-safe-system-tested-on-the-x-62a-vista-revolutionizes-flight-test/1683926452511463/

Video was too large to email in presentation – link above for video.

Link below for additional info.

https://aerospaceglobalnews.com/news/lockheed-martin-skunk-works-demonstrates-revolutionary-adaptive-flight-control-technology/

Pilot was asked to perform the same H2G maneuver, in the presence of a failed flap

SAFE corrects for the right flap surface failure and reduces pilot workload

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Continued Development

- Parameter Identification (PID) is an important topic across many disciplines including aerospace
- Knowledge of the physics of the aircraft can inform better design choices and increase flight stability, robustness, and performance
- Although post-flight data analysis is essential in deepening our understanding of aircraft physics, incorporating online learning provides far greater flexibility and real-time practicality

<u>Investigation</u>

- Single-Thread Attractive Manifold / Multi-Thread Attractive Manifold (S-TAM / M-TAM)
- Physics Informed Neural Networks

Explore new PID methods to learn/update physics models

SAFE Conclusions

- Bolt-On SAFE controller is a drop-in solution that adds robustness to traditional control techniques in the presence of uncertainties/nonlinearities
    - Lost/failed control surfaces exceed normal modelling-error bounds; however, the SAFE architecture automatically compensates to maintain safe, stable flight
- SAFE allows flight to the corner of the envelope, enabling learning algorithms to collect data sooner
- S-TAM / M-TAM provides solid theoretical guarantees of convergence, which make it a suitable candidate for online learning

SAFE is an enabling technology, allowing us to hit milestones sooner

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Overall Conclusions

- NATO research groups
  - AVT-424 – Active Flow Control – promising technology for specific platforms and missions
  - AVT-419 – Control Allocation – evaluation and maturation of improved algorithms
  - Continued collaboration with universities and small businesses
- SAFE IR&D – continuing deployment of the technology to our platforms, adding learning components to improve / update physics modeling

Lockheed Martin Aero continues technology development, both internally and with collaborators

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