National Aeronautics and Space Administration

# Integrated Control with Structural Feedback to Enable Lightweight Aircraft


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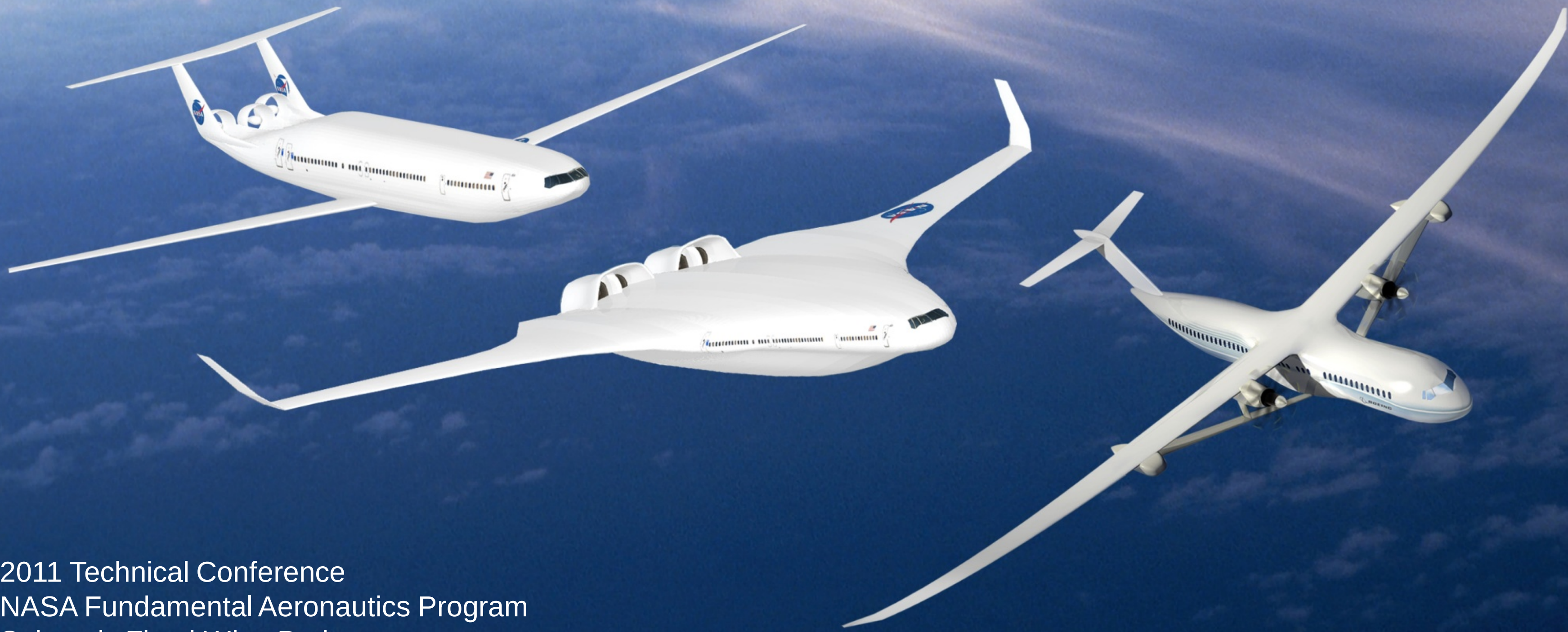


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Subsonic Fixed Wing Project
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# Agenda

- System Level Metrics
- Benefits of Active Structural Control
- Active Structural Control Research Areas
- Integrated Control for the Prevention of Critical Loads
  - Problem Statement
  - Control System Architecture
  - Simulation Studies
    - Approach
    - Results and Discussion
- Future Research

# NASA Subsonic Transport System Level Metrics

***…. technology for dramatically improving noise, emissions, & performance***

| CORNERS OF THE TRADE SPACE | N+1 (2015)*** Technology Benefits Relative to a Single Aisle Reference Configuration | N+2 (2020)*** Technology Benefits Relative to a Large Twin Aisle Reference Configuration | N+3 (2025)*** Technology Benefits |
|---|---|---|---|
| Noise (cum below Stage 4) | - 32 dB | - 42 dB | - 71 dB |
| LTO NOx Emissions (below CAEP 6) | -60% | -75% | better than -75% |
| Performance Aircraft Fuel Burn | -33%** | -50%** | better than -70% |
| Performance Field Length | -33% | -50% | exploit metroplex* concepts |

*** Technology Readiness Level for key technologies = 4-6

** Additional gains may be possible through operational improvements

* Concepts that enable optimal use of runways at multiple airports within the metropolitan areas

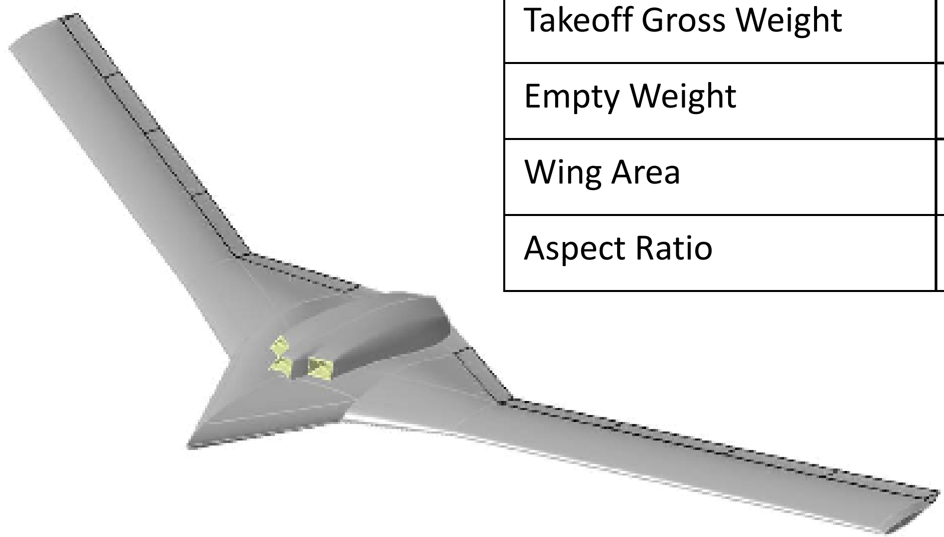
## SFW Approach

- Conduct Discipline-based Foundational Research
- Investigate Advanced Multi-Discipline Based Concepts and Technologies
- Reduce Uncertainty in Multi-Disciplinary Design and Analysis Tools and Processes
- Enable Major Changes in Engine Cycle/Airframe Configurations

# Benefits of Active Structural Control

- Reduction in aircraft fuel burn due to reduced structural weight
  - Reduced structural margins
    - Gust loads
    - Aeroelastic instabilities
- Gust loads and aeroelastic instabilities inherent in high lift-to-drag, high aspect ratio, low sweep wings (N+3 aircraft)
- One study has shown a 25% reduction in airframe weight through the use of active flutter suppression
  - "System Benefits of Active Flutter Suppression for a SensorCraft-Type Vehicle", Nicolai, Hunten, Zink, and Flick

| | |
|---|---|
| Takeoff Gross Weight | 96,000 lb |
| Empty Weight | 36,332 lb |
| Wing Area | 2445 $ft^2$ |
| Aspect Ratio | 14 |



# Research Areas

## Materials and Actuation

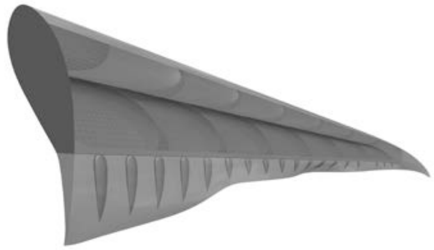
– Conformable mold-line
– Effector development

## Sensors

– Fiber optics
– Stagnation point sensors

Actively Controlled, Lightweight Structure

*Improved fuel burn, noise, and performance*



## Control Laws

– Unstable rigid body dynamics
– Unsteady aeroelastic effects (limit cycle oscillation, flutter, dynamic gust load response)
– Reduction of peak loads
– Wing shape optimization

## Test, Evaluation, and System Analysis

– Flight validated models and simulations
– Multi-disciplinary design guidelines
– Uncertainty analysis and propagation

# Fiber Optic Sensor Development

- Objective: enable a high density of real-time measurements of deflection, rotation, bending moment, torsion, and mode shape
  - Validate method and equations
  - Determine accuracy of measurements
  - Determine optimal fiber placement
- Approach: capture data from ground and flight tests on aircraft and simple test articles to investigate fundamental principles and draw comparisons to other sensor technologies

*Ground Test of Global Observer wing*

# Fiber Optic Sensor Development

- Results: data captured in flight and ground tests
  - Good results for bending deflection of simple test articles and a full scale UAV
- Remaining Work: progression to more complicated structures, validate loads measurements, increased sample rate, increased resolution, and multi-core fiber
- Significance: enable structural weight reduction
  - Structural feedback to control system (shape and loads)
    - Maneuver and gust load alleviation
    - Active control of aeroelastic instabilities
    - Structural health monitoring

*Swept Plate Undergoing Test*

# Aerodynamic Force Sensor Development

- Objective: enable real-time measurement of external forces acting on the aircraft in the presence of flow separation through direct measurement of stagnation point
  - Model generation
  - Parameter identification
  - Stagnation point control
    - Loads, aeroelastic instabilities

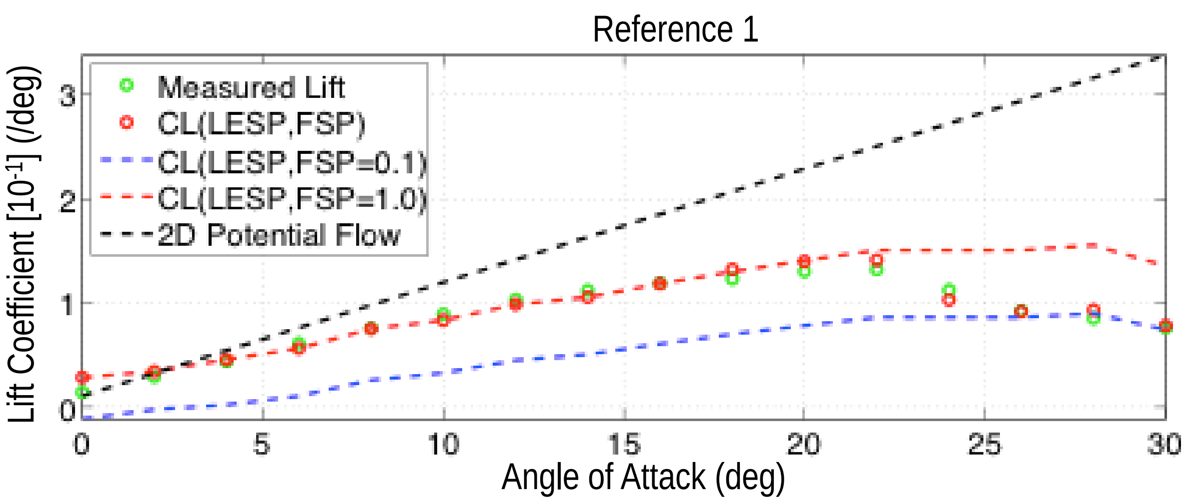
- Approach: progression from open-loop observability and validation to closed loop control of stagnation point location

*Aerostructures Test Wing*

# Aerodynamic Force Sensor Development

- Results: validation of stagnation point to sectional forces through wind tunnel tests and open-loop flight test (observability)

- Remaining Work: close the loop around stagnation point sensors to check controllability




- Significance: enables structural weight reduction, optimization of sectional forces to reduce drag, and precise lift control during takeoff and landing
  - Direct measurement of external forces without the associated structural lag
  - Indirect measurement of drag
  - Provides an observable for the state of separated flow around stall conditions
  - Detection and diagnosis of shock/boundary-layer interaction and separation-induced load fluctuations

# Integrated Control for the Prevention of Critical Loads

| NASA DFRC | NASA ARC |
|---|---|
| Brian Taylor | Susan Frost |
| John Burken | Khanh Trinh |
| Christine Jutte | |

# Problem Statement


*Roll Moment Achieved*

Structural Limit Exceeded

*Roll Moment Achieved*

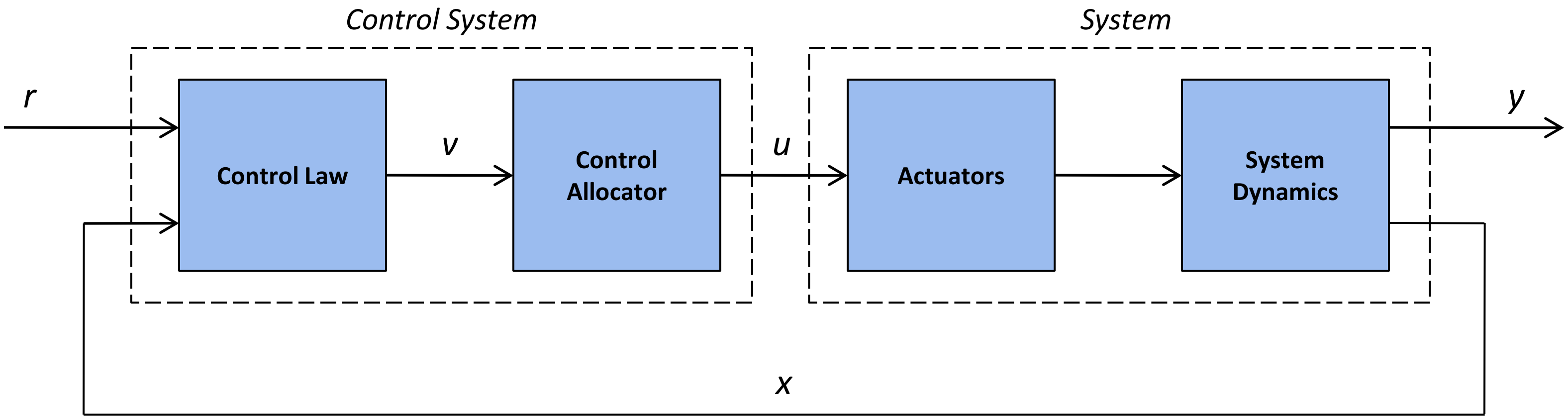
Structural Loads *Within Limits*

- Use active structural feedback to determine the optimal control surface positions to:
  - Meet commanded rigid body moments
  - Minimize structural loads
  - Ensure that structural loads do not exceed limits

- Optimal control allocation with structural feedback is a potential solution

# Optimal Control Allocation

- Separate the regulation task from the control allocation task
- Mixed optimization to solve multiple objectives simultaneously




*Conventional Control Law with Optimal Control Allocation (ref. 2)*

# Control Allocation Objectives

- Meet commanded rigid body moments *(v)*
  - Solve for surface positions (*u*) such that $v = Bu$
- Need both structural feedback <u>and</u> predictive portion similar to the rigid body moments and the control effectiveness *(B)* matrix
  - Measured load *(M)* and incremental load due to incremental control surface deflection *(T)*

$$L = M + Tu$$

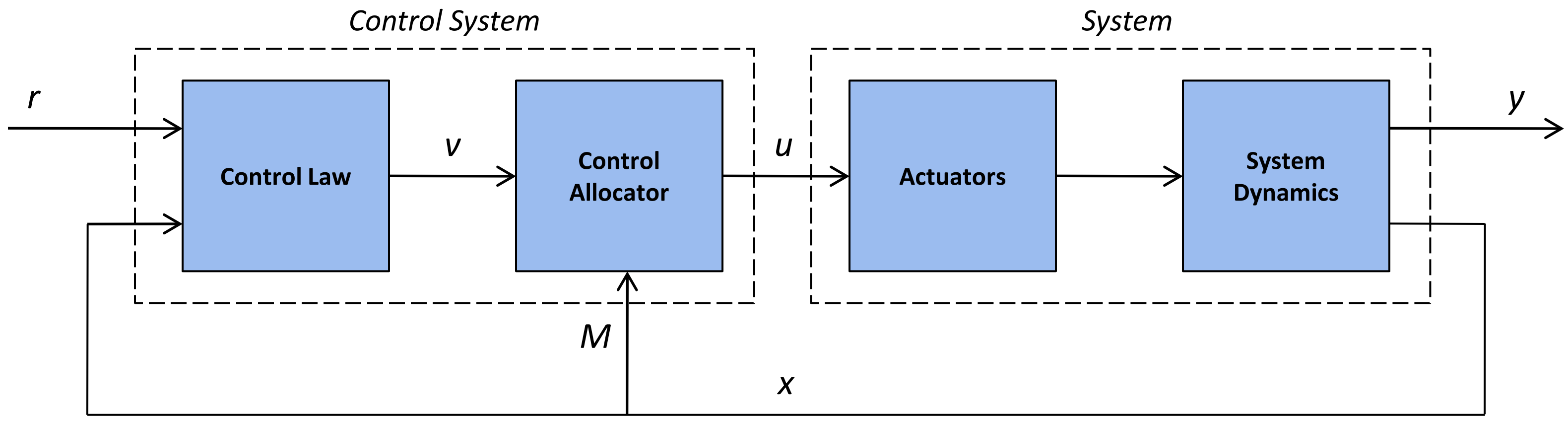
- Minimize structural loads
- Ensure that structural loads do not exceed limits
  - Treated like control surface saturation
- Cost function:

$$J = \left\| Bu - v \right\| + \gamma \left\| M + Tu \right\|$$

Subject to:

$$u_{\min} \le u \le u_{\max} \qquad (M + Tu) \le L_{\max}$$

# Control Allocation Diagram




*Structural Feedback Control Law with Optimal Control Allocation*

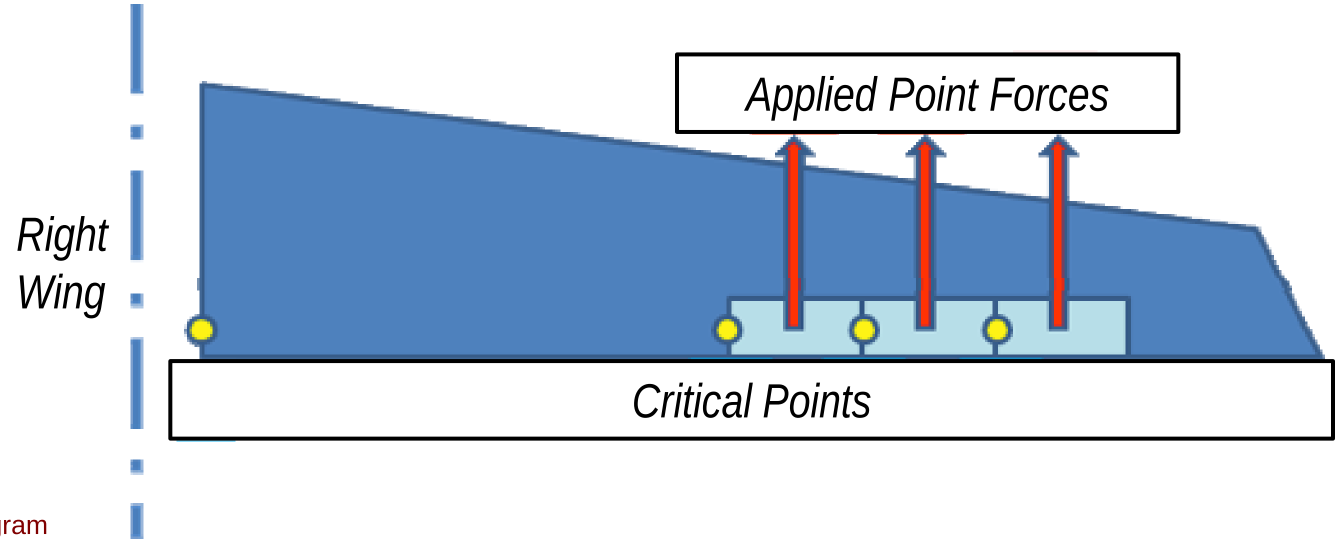
- Feedback of measured load to control allocator
- Inclusion of the *T* matrix
  - Computed from FEM code
  - Lookup table
  - Parameter estimation

$$T = \frac{\text{Incremental Load}}{\text{Incremental Deflection}}$$

$$B = \frac{\text{Incremental Moment}}{\text{Incremental Deflection}}$$

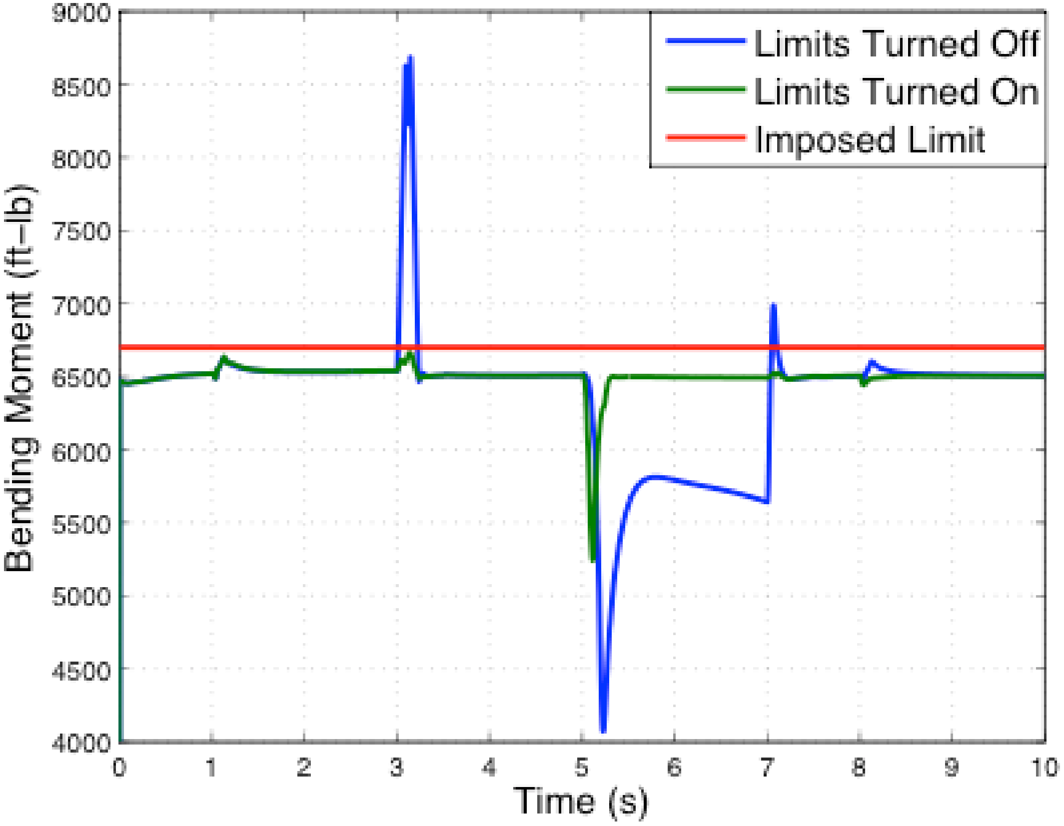
# Simulation Study Approach

- Modified Generic Transport Model (GTM) simulation
  - 6 ailerons, 4 elevators, 2 rudders
  - FEM of wing, horizontal tail, and vertical tail
  - "Critical points" at inboard edge of control surfaces and roots
  - Distributed lift force over entire wing/tail and point forces due to control surfaces
- Roll maneuver
  - Load control on and off with load limits set low enough to require change in allocation
    - Same rigid body motion with reduction in load at critical point

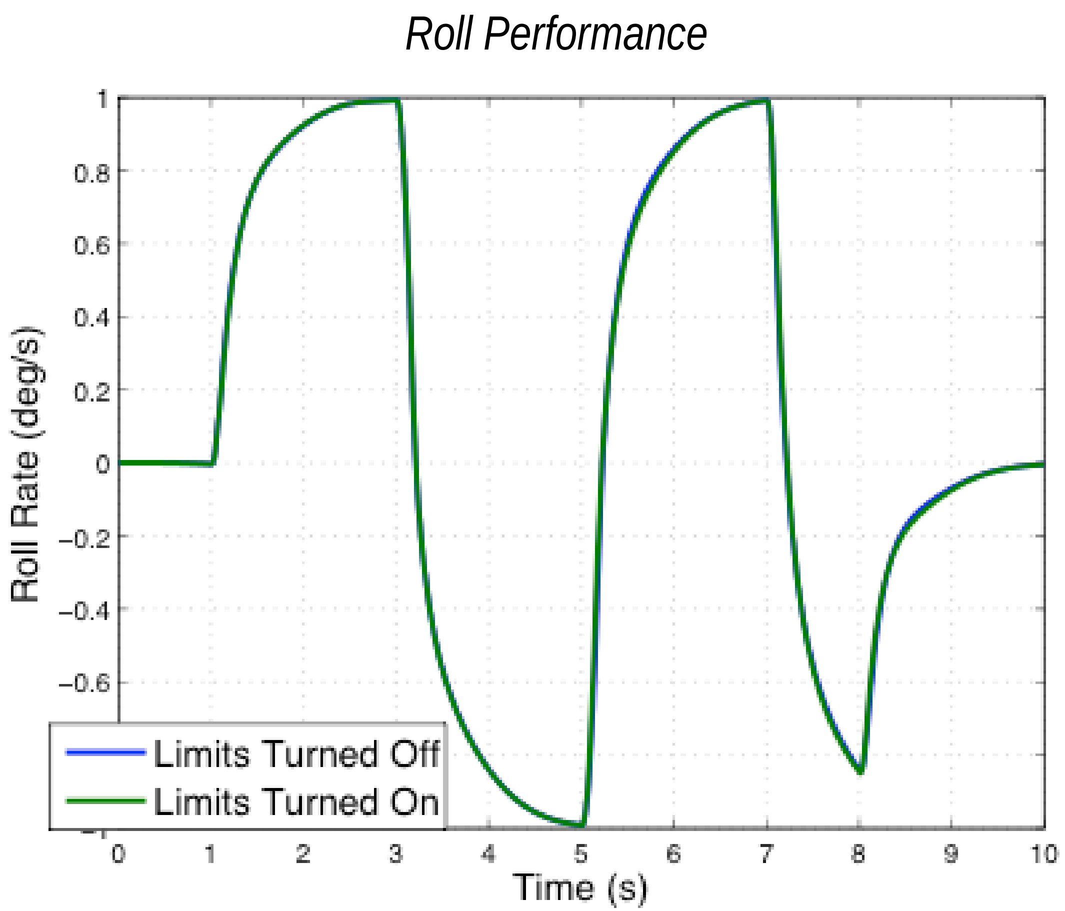


# Simulation Study Results

*Outboard Aileron Bending Moment*



# Simulation Study Results



# Simulation Study Discussion

- Roll moment generation moved from outboard aileron surfaces to inboard surfaces
  - L1 norm optimal control allocation used for study
  - L2 norm would more evenly distribute demand
  - All control surfaces that generate roll moment available (split elevator and rudder)

- Roll performance maintained without violating load limits

- Can be used to:
  - Enable optimal control allocation on existing aircraft
    - Control surface commands constrained not to exceed existing load limits
  - Enable lighter weight structure on future aircraft
    - Reduce future load limits while still meeting performance demands
    - Extension to algorithm for gust load alleviation

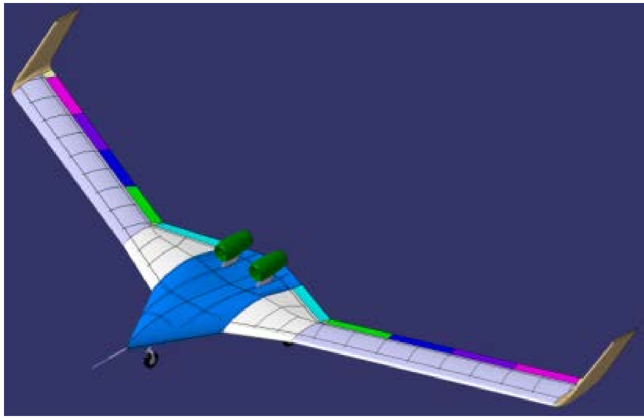
# Next Steps

- Study *T* matrix assumptions and accuracy necessary for flight
- Extension of algorithm for gust load alleviation
  - Gust load alleviation literature survey
  - Incremental load per incremental gust
    - *"G"* matrix
  - Need measurement of gust
  - Addition of gust loads into optimal allocator objectives
- Improved sensor fidelity
  - Delays inherent in each sensor
- Hardware test of algorithm and feedback

# Future Research

- Characterize input and response of structure in flight
  - Stagnation point sensors, fiber optics, strain gages, accelerometers, photogrammetry
- Create and release validated models and simulations
- Active load control, gust load alleviation, and flutter suppression
  - Dedicated surfaces
  - Demands spread across all surfaces
- Passive aeroelastic tailoring
- Develop analysis techniques
- Validate design and optimization tools using flight data

*NASA F-18 FAST*



*Multi-Utility Technology Testbed*

NASA

# Nomenclature

| Symbol | Definition |
|---|---|
| r | Commanded rates |
| v | Commanded moments |
| u | Commanded surface positions |
| y | Aircraft response |
| x | Observed aircraft states |
| M | Measured load |
| L | Predicted future load |
| T | Incremental load per incremental surface deflection |
| B | Incremental moment per incremental surface deflection |
| G | Incremental load per incremental gust |
| $\gamma$ | Weighting matrix |
| $u_{max}$ | Maximum surface position |
| $u_{min}$ | Minimum surface position |
| $L_{limit}$ | Load limit |
| J | Cost function |

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## Acknowledgements


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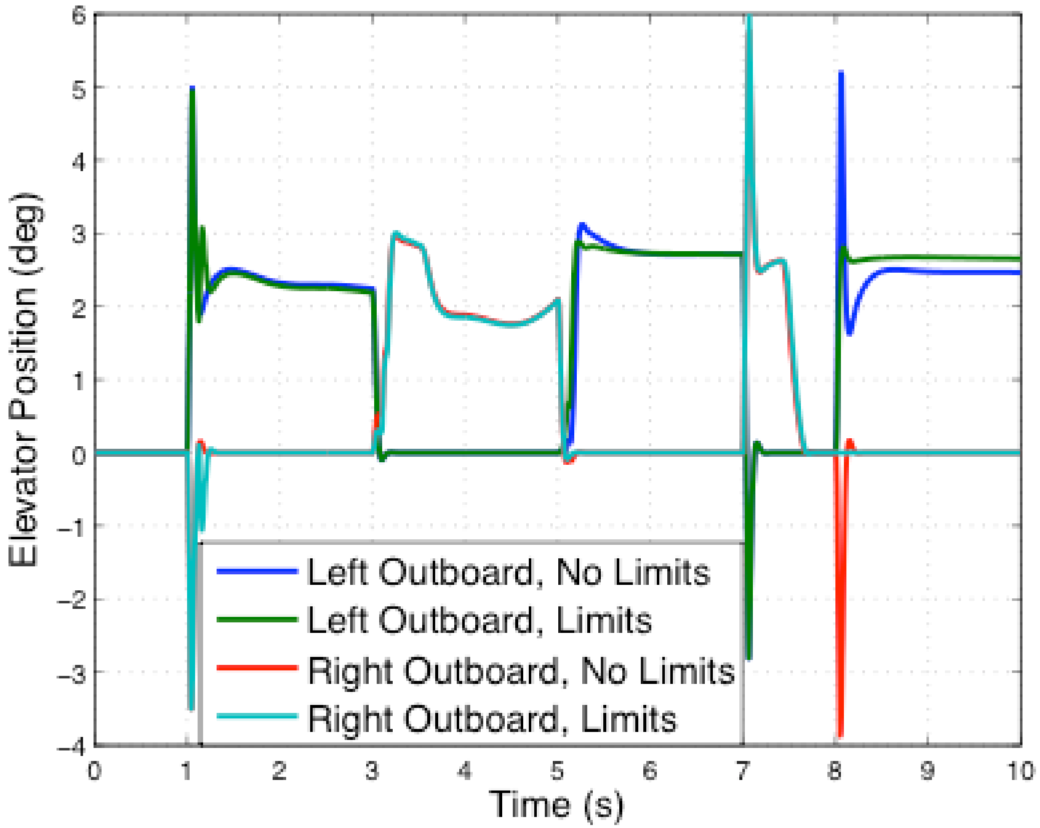
# Backup Slides

- Elevator outboard



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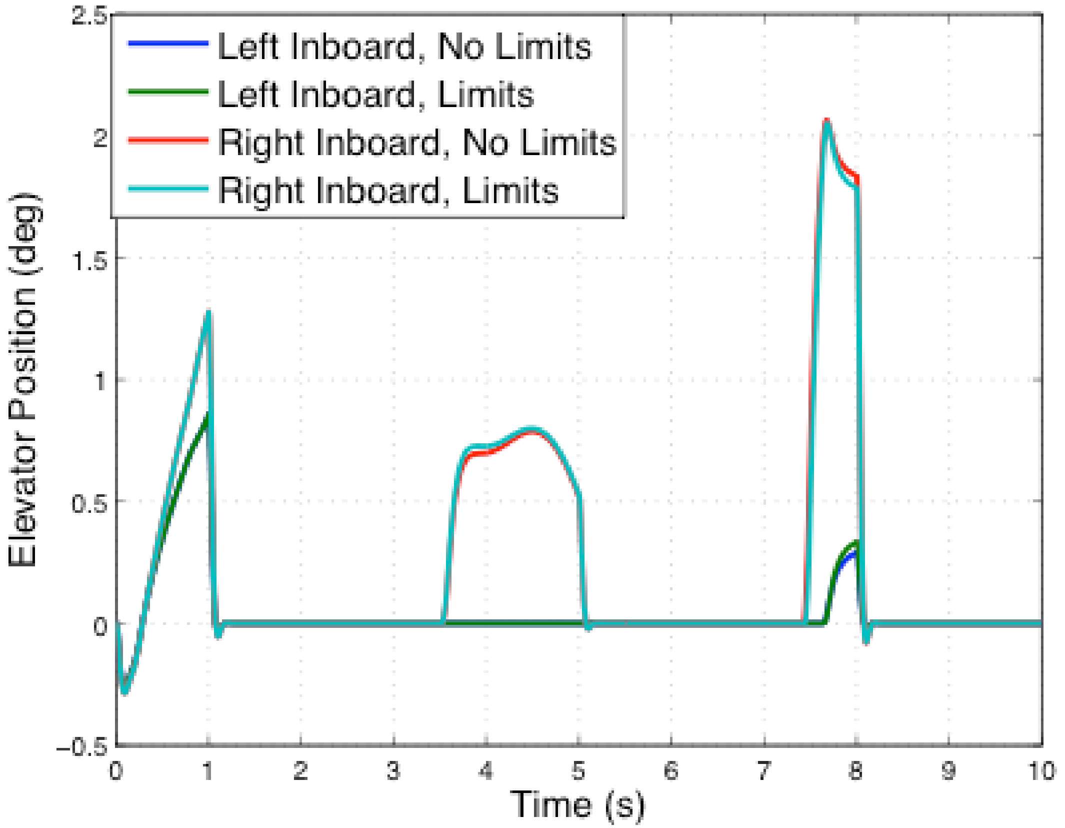
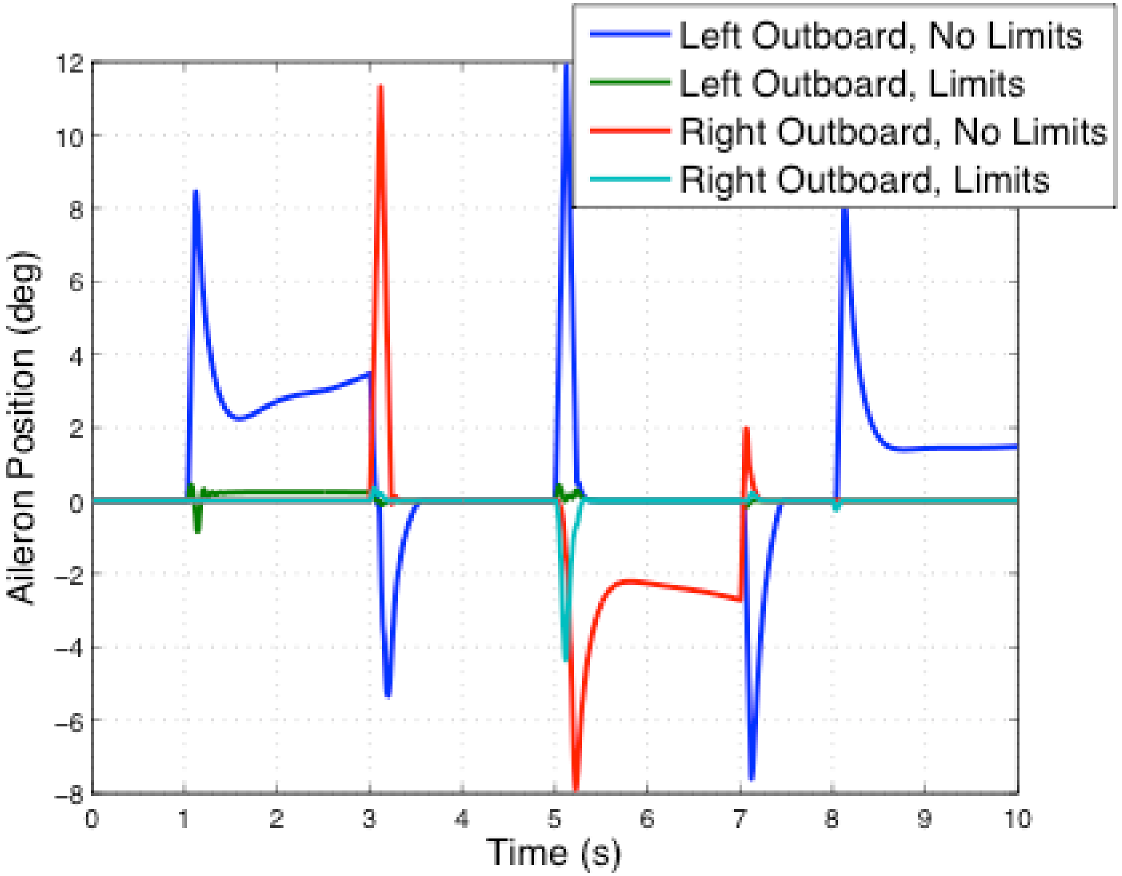


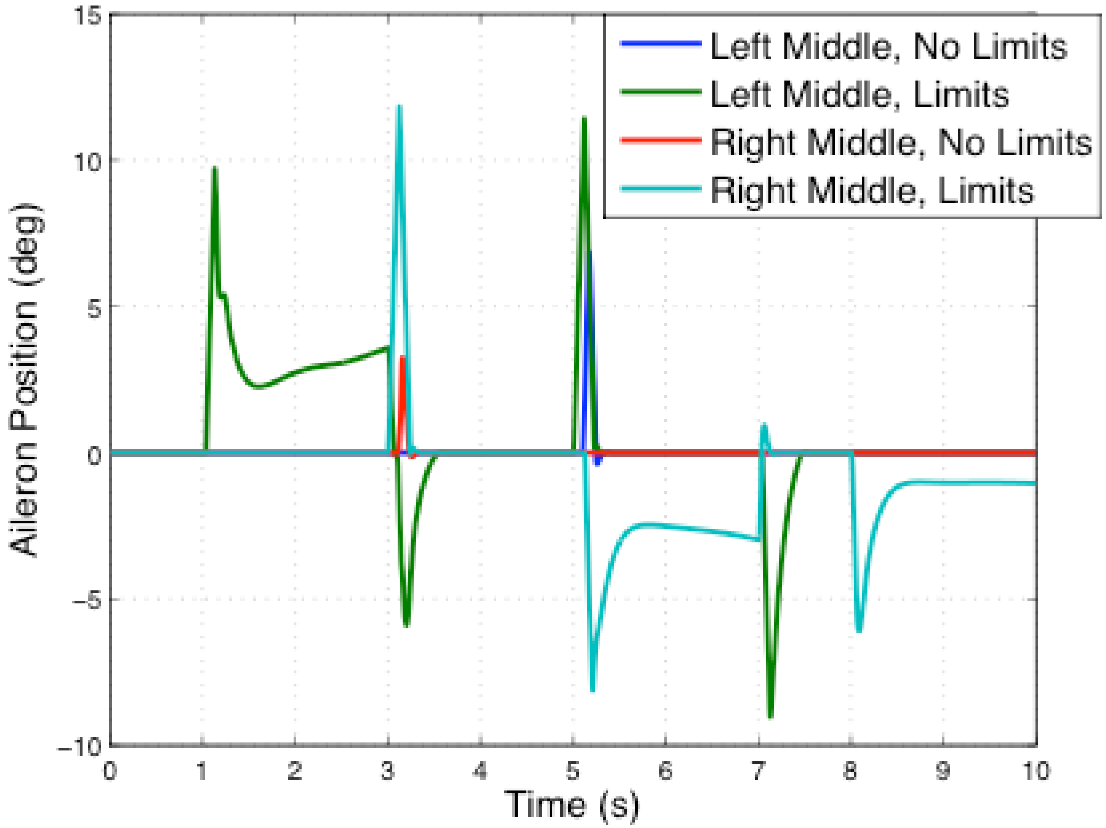
# Backup Slides

- Aileron outboard



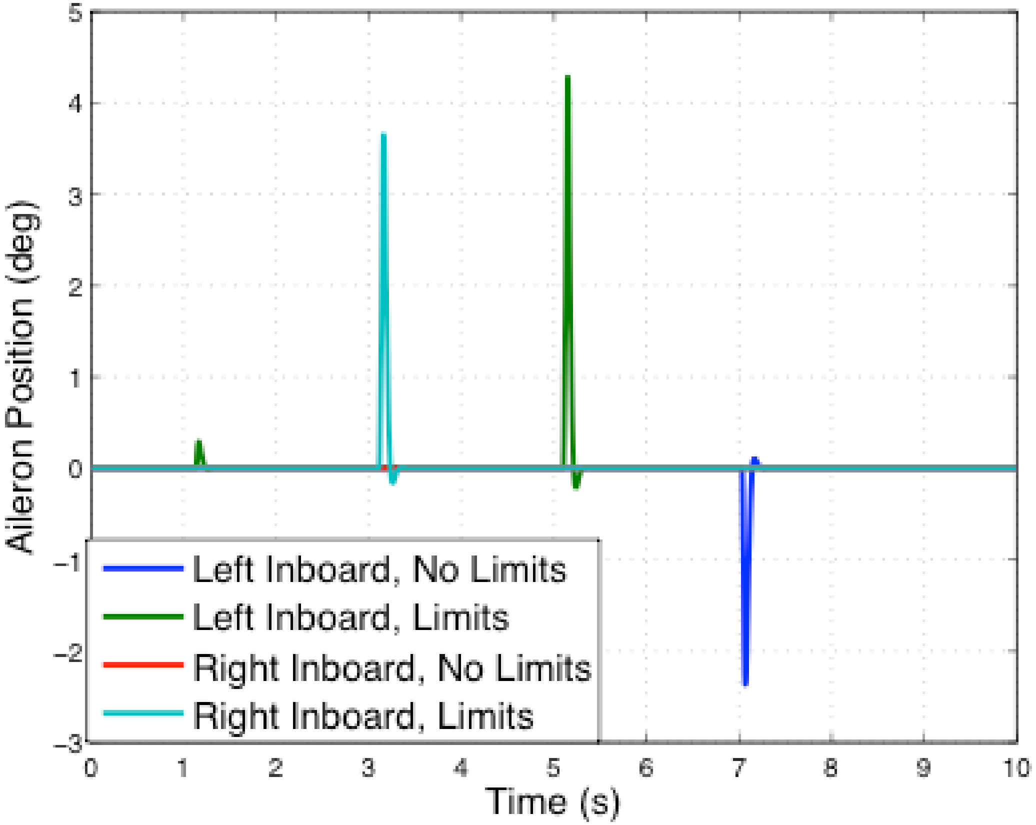
# Backup Slides

- Aileron middle



# Backup Slides

- Aileron inboard



# Backup Slides

- Rudder upper and lower