Advanced Control and Autonomy Research

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NASA – DLR Meeting at NASA Ames
March 14, 2017

Outline

- **Overview of ACES Group – Dr. Nhan Nguyen**
- **UAS Autonomy Research – Dr. Corey Ippolito**
- **Stall Recovery Guidance Research – Dr. Thomas Lombaerts**
- **Flexible Aircraft Flight Control Research – Dr. Sean Swei**

Advanced Control and Evolvable Systems Group

- Advanced Control and Evolvable Systems (ACES) Group (21 people) within the Intelligent Systems Division (code TI) conducts advanced GNC research and multidisciplinary vehicle dynamic modeling and simulations

- > 90% of research are aeronautics with some space-related GNC

- Collaborate with other NASA centers (AFRC, LaRC, GRC), other government agencies (FAA, DHS), industry (Boeing and small business companies), and academia (U.S. universities and TU Delft)

Intelligent Adaptive Flight Control

- **Core expertise of ACES group**

Intelligent Flight Control System (IFCS) 2003 – 2006

- Sigma-Pi neural network MRAC (Model-Reference Adaptive Control)
- Team: NASA AFRC, NASA ARC, IV&V, Boeing

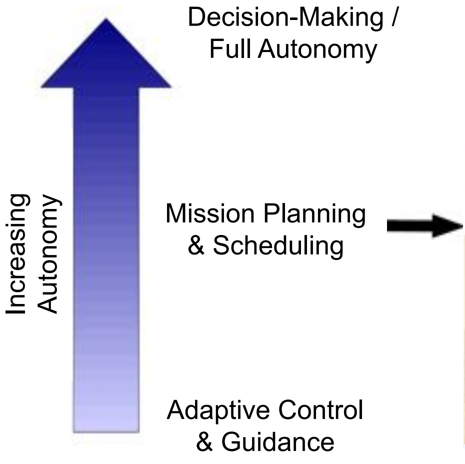
Integrated Resilient Aircraft Control (IRAC) 2007 – 2011

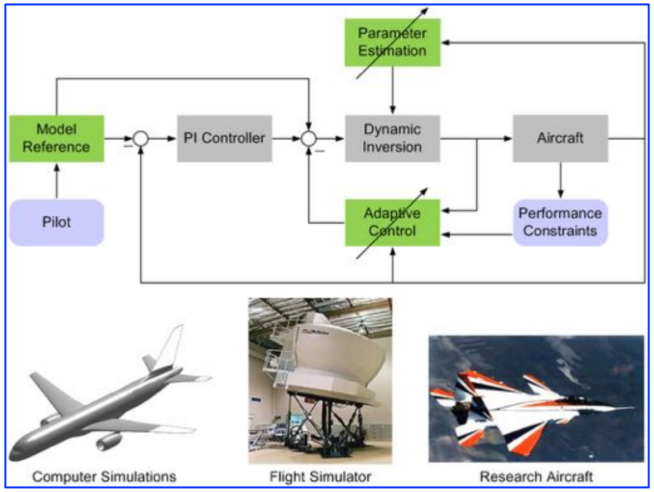
- NASA simplified MRAC / optimal control modification
- Team: NASA AFRC, NASA ARC

Adaptive Control & Guidance for Vehicle Autonomy

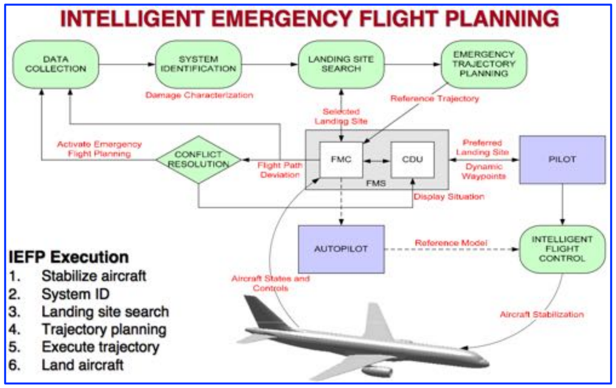
Adaptive control as enabler for vehicle autonomy

- Adaptation through closed-loop control and mission management
- Integration with vehicle adaptive physical hardware & software
- Interactions with other domains (human-machine interactions, prognostics, etc.)





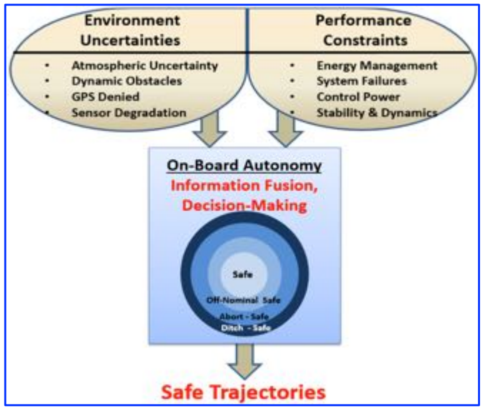
Intelligent Adaptive Flight Control



IEFP Execution

1. Stabilize aircraft
2. System ID
3. Landing site search
4. Trajectory planning
5. Execute trajectory
6. Land aircraft

Intelligent Flight Planning



UAS Decision-Making

Autonomy

Performance Adaptive Aeroelastic Wing (PAAW)

Overview

Conduct multidisciplinary research to develop advanced technologies for wing shaping control to reduce fuel consumption and improve safety of high aspect-ratio flexible wing transport aircraft

Impacts

- 1% – 6% drag reduction which could translate into as much as $0.2B – $1.3B fuel savings (www.transtats.bts.gov/fuel.asp)
- Reduce aircraft weight and gust loads
- Improve passenger comfort and enable safe operation of flexible wing transport aircraft

Collaboration

NASA AFRC, NASA LaRC, Boeing, Scientific Systems Company Inc., U of Washington, Wichita State U, Technical University Delft

Integrated Vehicle Multidisciplinary Research Capabilities

Multi-Fidelity Modeling
- Multi-fidelity aero modeling (Cart3D, Overflow, Lava, Vorlax, Vspaero)
- Coupled FEM (Beam3D, NASTRAN) with aero codes
- Aeroelasticity / Aeroservoelasticity (ASE)

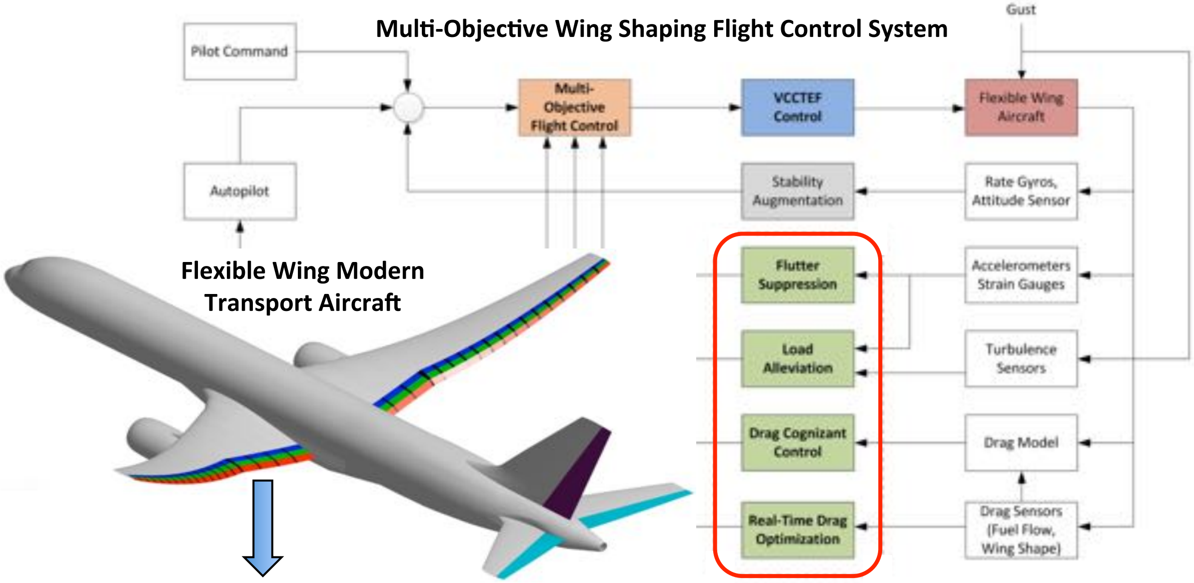
ASE – Flight Dynamics
- Coupled ASE – rigid aircraft flight dynamics
- Gust modeling
- Actuator dynamics of ASE control effectors

Multidisciplinary Optimization
- Aerodynamic design optimization for drag reduction
- MDO for drag minimization, load alleviation, and active ASE control

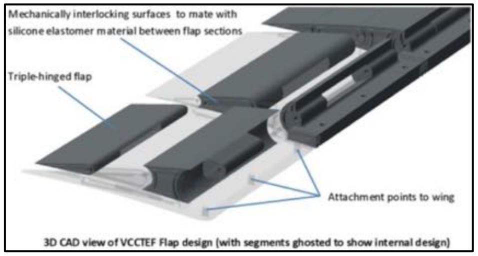
ASE Flight Control
- ASE control (flutter suppression, load alleviation)
- multi-objective flight control
- Real-time drag optimization

Performance Analysis
- Design trade-study
- Mission analysis / trajectory optimization to minimize fuel burn

Control Actuation
- VCCTEF / continuous leading edge slat
- Distributed control surfaces
- Other novel actuation concepts

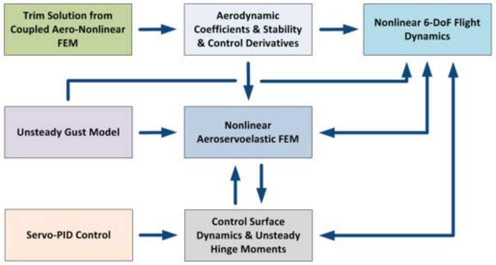

Multi-Objective Wing Shaping Flight Control System

Flexible Wing Modern Transport Aircraft



Variable Camber Continuous Trailing Edge Flap (VCCTEF) Drag Reduction Technology

Wind Tunnel Validation



Aeroservoelasticity (ASE) Modeling

X-56A Collaboration with NASA AFRC

Mission Adaptive Digital Composite Aerostructure Technologies (MADCAT)

Objective:
Develop a revolutionary aerostructure concept by combining the lattice-based discrete construction and the multi-objective optimal flight controls to realize mission adaptive and aerodynamically efficient future air vehicles.

Approach:
To leverage emerging digital composite manufacturing and fabrication methods and utilize the “building-block” strategy to build high stiffness-to-density ratio, ultra-light aerostructures that can provide mission adaptivity for varying flight conditions.

Status:
A scaled UAV model, capable of wing morphing, was built and flight tested successfully.

Funding & Duration:
This project is funded by ARMD CAS Project. FY16-FY17.

Safe, Autonomous, and Routine Operation of Small-UAS in High-Density Low-Altitude Urban Environments

Corey Ippolito, Kalmanje Krishnakumar

December 5, 2016

SAFE50 Project Overview

Purpose

- Investigate onboard vehicle autonomy for safe, autonomous and routine small-UAS operations in high-density low-altitude urban environments, from the viewpoint of regulatory stakeholders and traffic system operators such as UTM.

Goal

- Develop vehicle-centric autonomy requirements allowing safe operations
- Investigate the trade-space (including capabilities, challenges, implications, and alternatives)
- Incorporate and disseminate into UTM for TCL-3, TCL-4

Approach

- Top-down analysis, requirements-driven approach
- Develop prototypes, perform simulation and flight testing experiments, work with external partners

Motivating Scenario and Characteristics

Through out the day, thousands of operators and vehicles utilize the airspace above the city. UAS requests appear randomly throughout the day, requesting navigation between random location/address within in the city.

- Urban canyons
- Constrained spaces
- High-density
- High-demand
- Large-scale concurrent operations
- Operating over high-valued assets

Scope and Definitions

- Routine Operations
- Small Unmanned Aerial Systems (UAS)
  - Mass up to 25 kg to 150 kg *
  - Airspeed up to 40 m/s *
- Low-Altitude Operations
  - Altitude up to 200m or 400m **
- High-Density Urban Environments
  - "Non-trivial density" of humans, human structures, infrastructure, and competing air traffic
  - Includes residential/commercial/high-rise buildings, towers, roads, bridges, railways, manned aircraft (particularly rotorcraft), and other UAS
  - Density metrics to be defined, may include
    - Population density greater than 1,000 people per square mile ***
    - Perhaps a minimum threshold UAS capacity per city block, such as 10 UAS per city block

NASA UAS Classification Matrix*			
Type	Model or sUAS	sUAS	UAS
Category	I (1)	II (2)	III (3)
Weight Limit	≤ 25 kg	25-150 kg	> 150 kg
Airspeed Limit	≤ 40 m/s	≤ 100 m/s	> 100 m/s

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* *per NASA NPR 7900.3C, Appendix I*

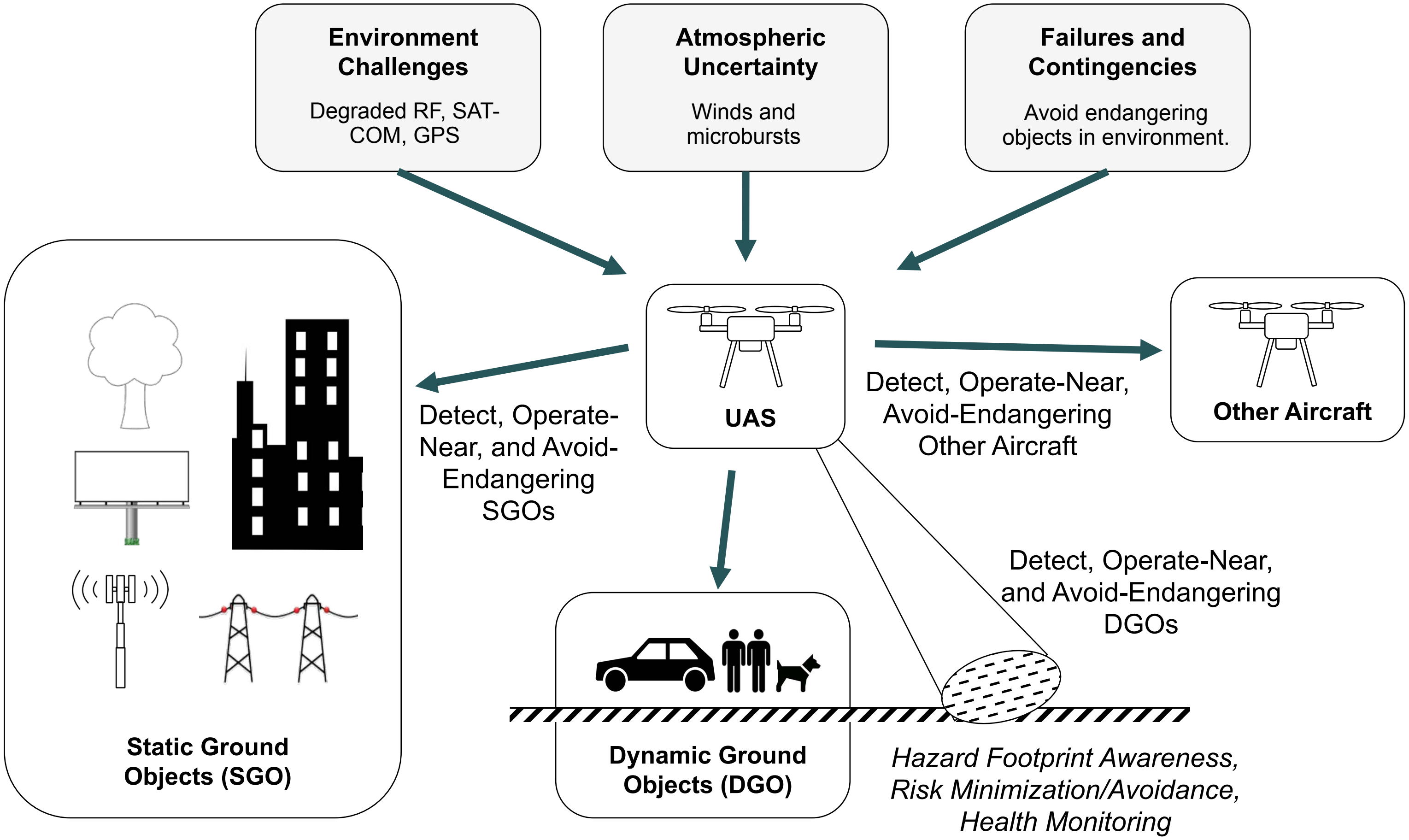
** *per U. S. Class G Airspace, typ. below 700ft/1200ft*

*** *per Geographic Areas Reference Manual (GARM), U.S. Census Bureau, 1994*

Challenges for High-Density Urban Operations

- Flight operations occur almost entirely beyond RF communications line-of-sight from ground operators to the vehicle. Limited point-to-point or satellite line-of-site. Need for Autonomy.
- Atmospheric uncertainties may have major impact on safety.
- Flight operations occur in a GPS-denied (or at-best a GPS-degraded) environment. Limited satellite line-of-site.
- Obstacles and hazards are not known with certainty ahead of time. Autonomous onboard see-and-avoid may an onboard vehicle requirement.
- Vehicle system failures has major impact on safety (high failure rates, single-string architectures).
- Real-time ground-based surveillance is not easily accomplished. Separation assurance may be an onboard vehicle autonomy requirement.

SAFE50 Vehicle Autonomy Requirements



Environment Challenges

Degraded RF, SAT-COM, GPS

Atmospheric Uncertainty

Winds and microbursts

Failures and Contingencies

Avoid endangering objects in environment.

UAS

Other Aircraft

Detect, Operate-Near, Avoid-Endangering Other Aircraft

Detect, Operate-Near, and Avoid-Endangering SGOs

Static Ground Objects (SGO)

Detect, Operate-Near, and Avoid-Endangering DGOs

Dynamic Ground Objects (DGO)

Hazard Footprint Awareness, Risk Minimization/Avoidance, Health Monitoring

- Detect : equivalent to ‘see’ or ‘sense’, cooperative or noncooperative, technology limits, SWaP constraints, cost implications
- Operate-Near : more stringent than ‘avoid’
- Avoid-Endangering : responsibility of risk and damage assigned to vehicles and operators

Tall-Poles and Research Focus

- Detection of objects (static, dynamic, other air vehicles)
- Classification of objects (as needed to satisfy requirements)
- Relative control to objects
- Decision making under uncertainty
- Resilience to wind gusts and micro-weather effects
- Resilience to onboard failures
- Risk minimizing nominal/off-nominal control
- Alternative/augmentations to GNSS-derived position, navigation, and timing

Approach

Environment Uncertainties

- Atmospheric Uncertainty
- Dynamic Obstacles
- GPS Denied
- Sensor Degradation

Performance Constraints

- Energy Management
- System Failures
- Control Power
- Stability & Dynamics

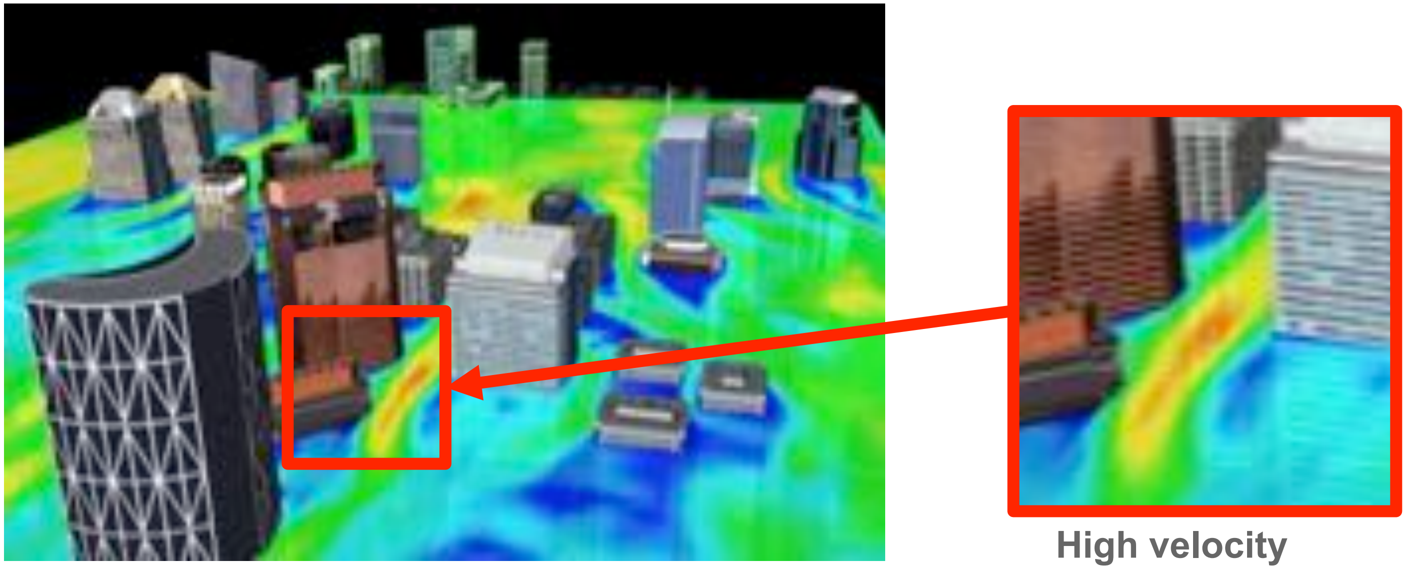
On-Board Autonomy

Information Fusion, Decision-Making

Safe Trajectories

Research Challenges

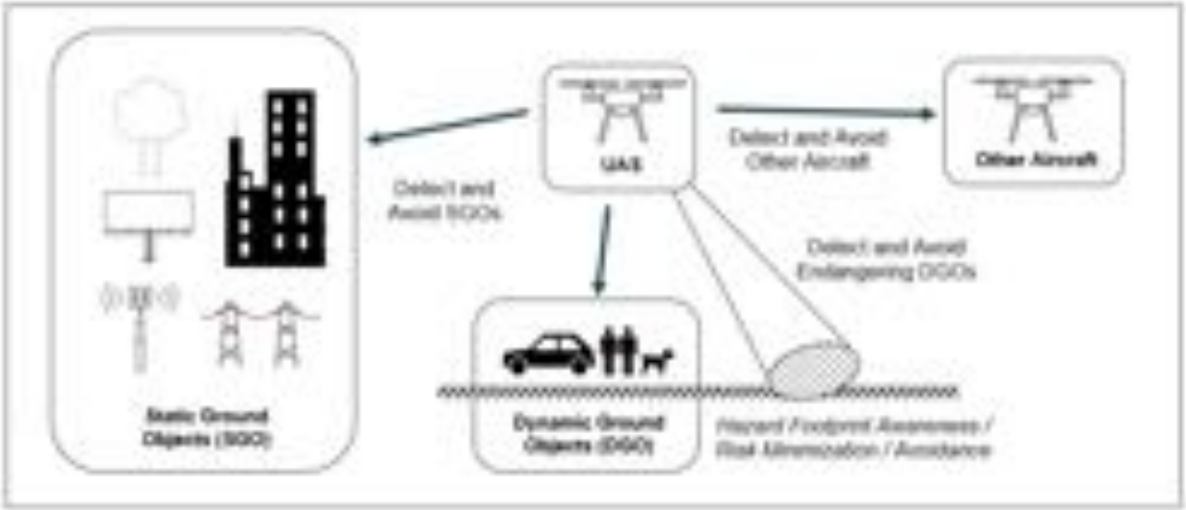
1. UrbanScape Wind Uncertainties



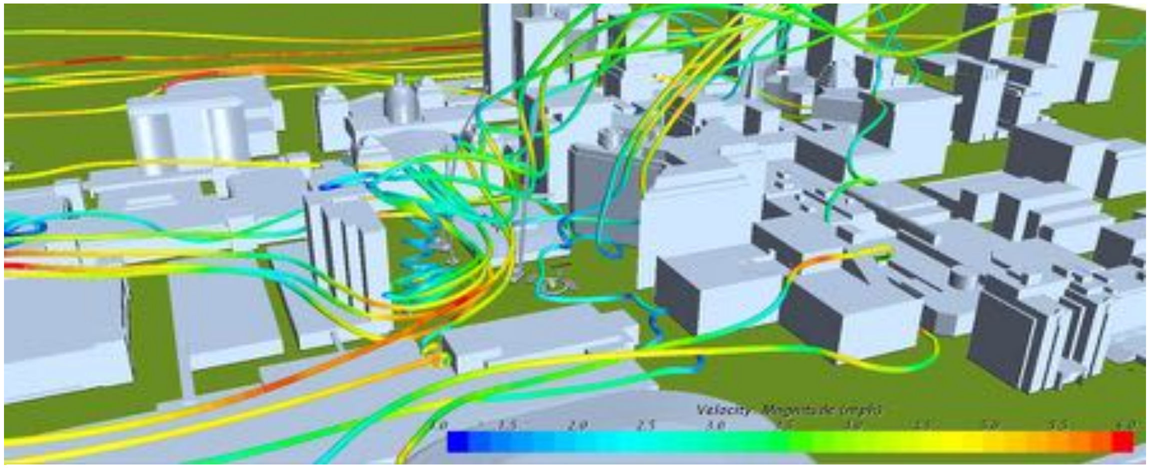
High velocity region

2. GPS Denied/Degraded

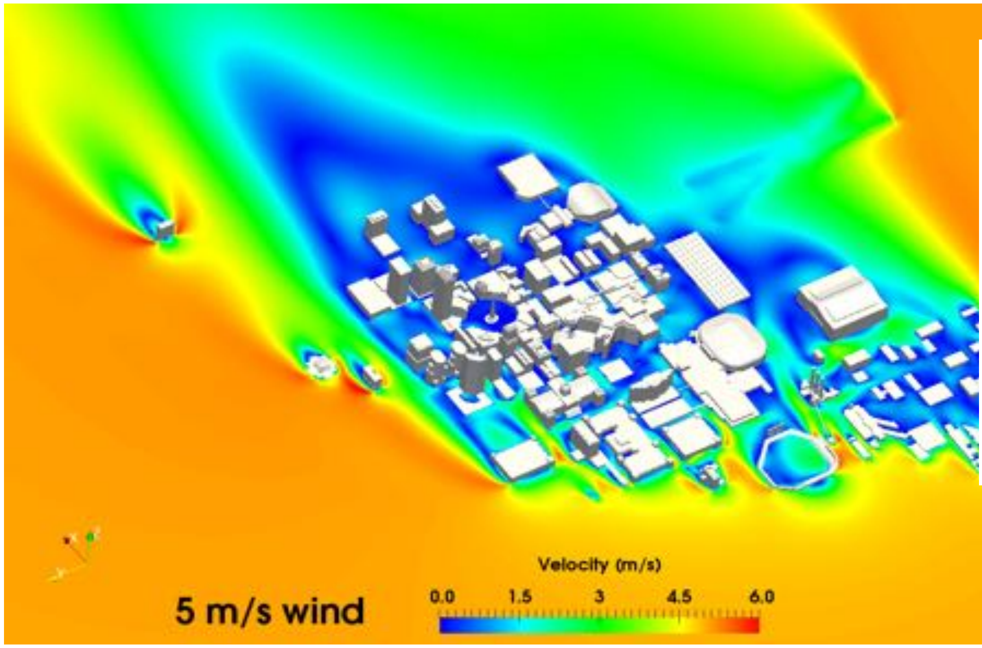
3. Static/Dynamic Obstacles

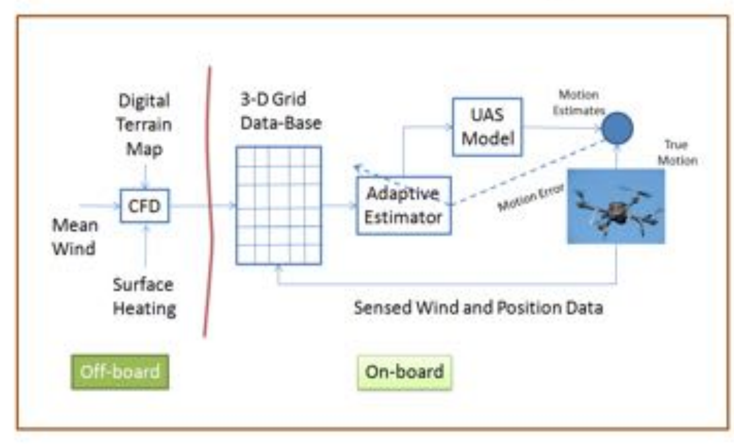


UrbanScape Wind Uncertainties

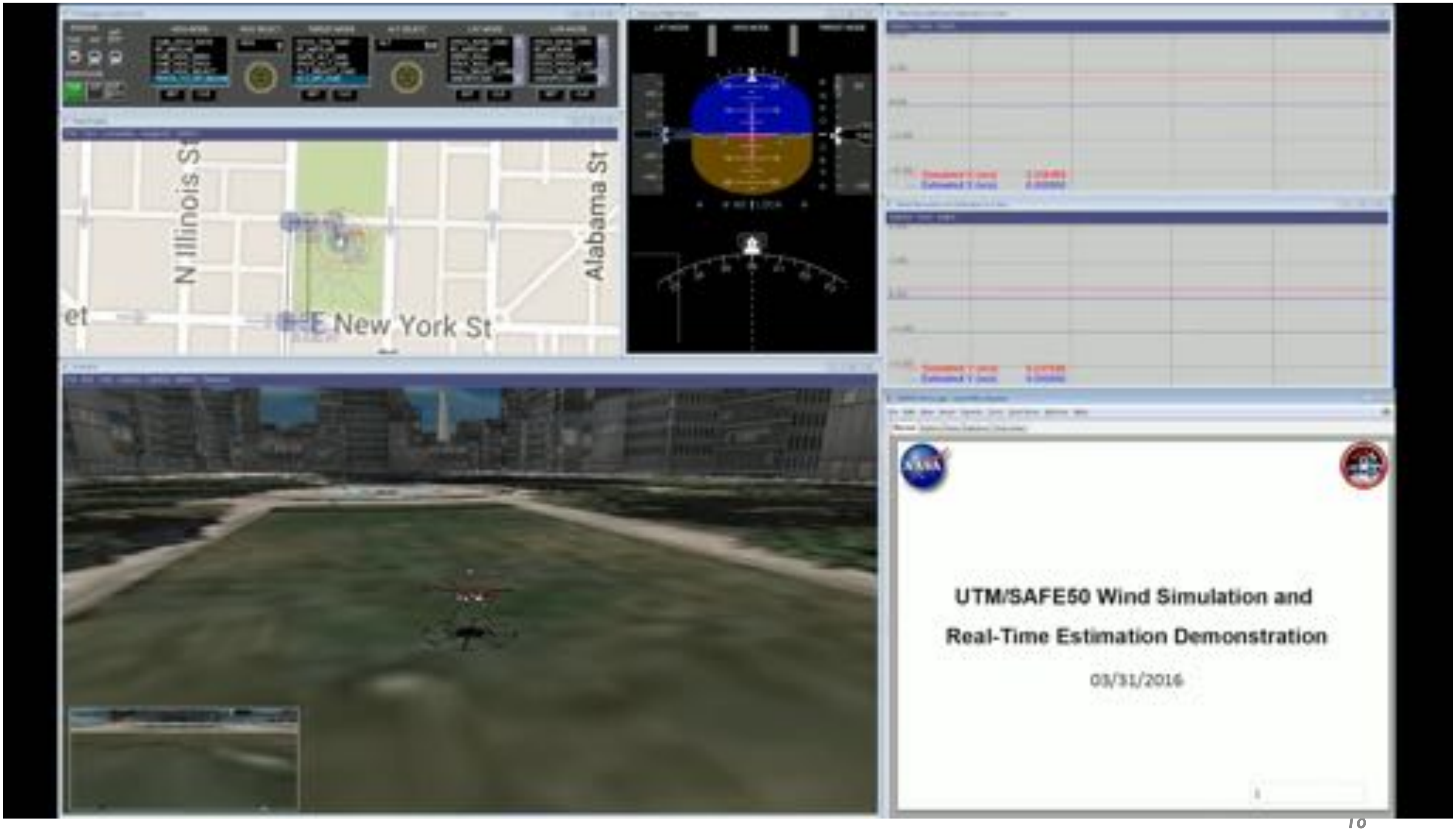


Urban Architecture and CFD Simulation of Wind Profiles.





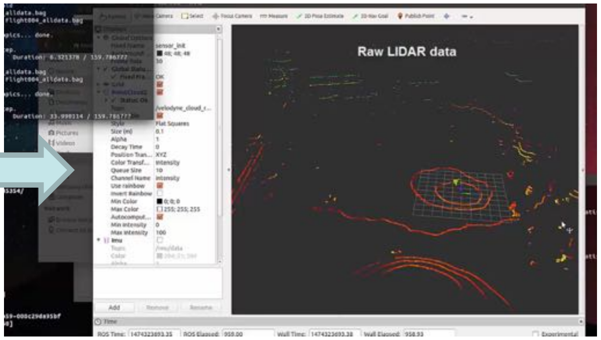
UrbanScape Wind Uncertainties

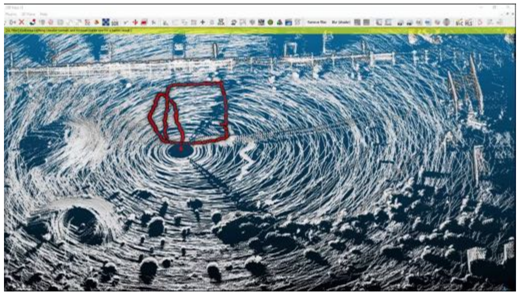


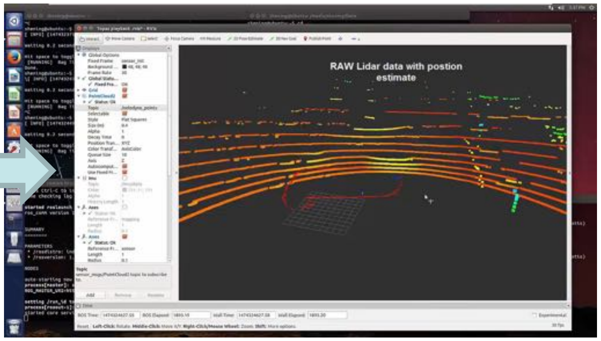
UTM/SAFE50 Wind Simulation and Real-Time Estimation Demonstration

03/31/2016

GPS Denied/Degraded Navigation

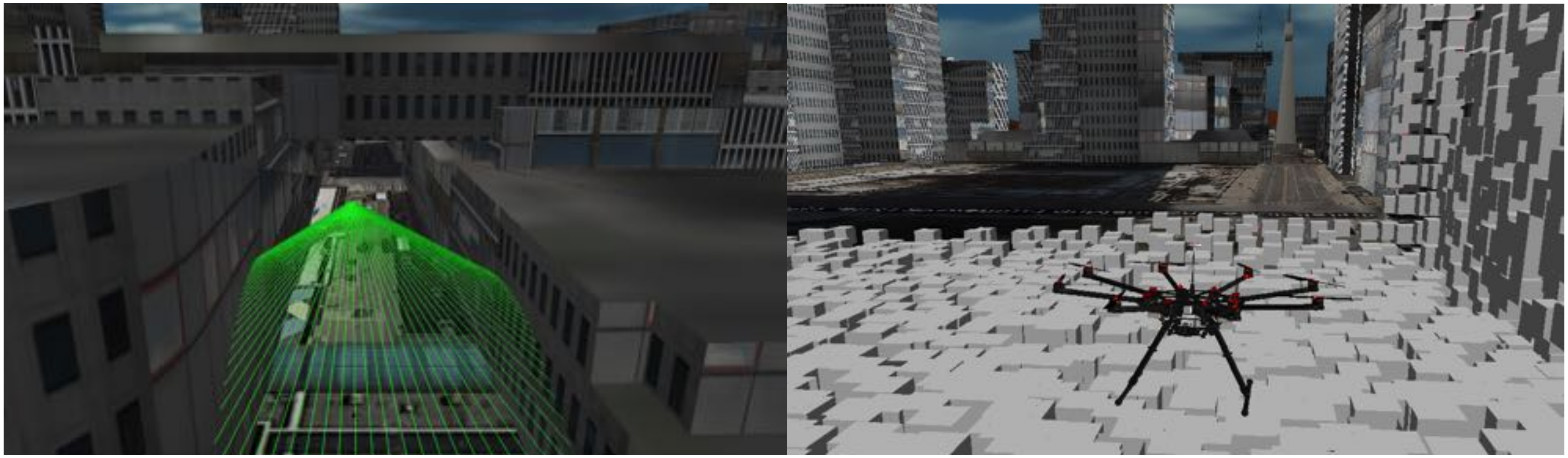


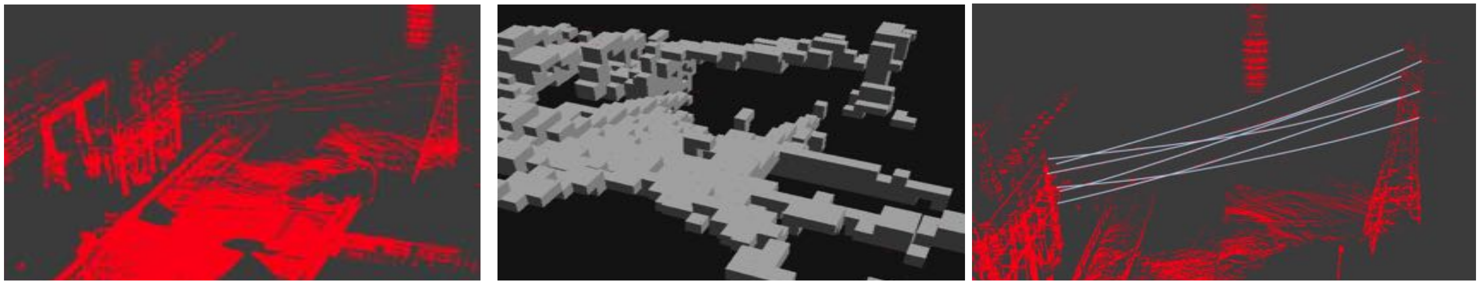




Static/Dynamic Obstacles

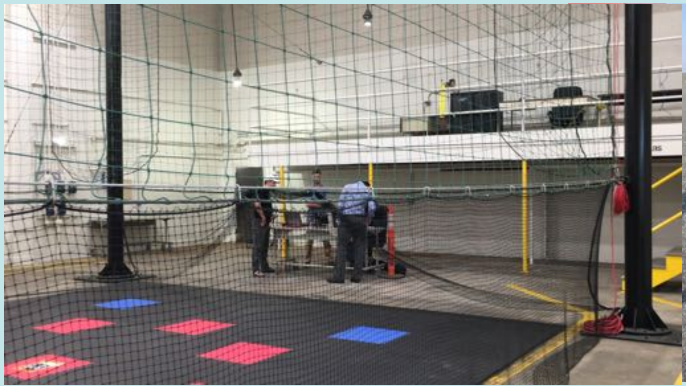
LiDAR Data and Voxel Representation





Powerline Identification and Reconstruction. Raw LiDAR point clouds (left), voxel processing (middle), reconstructed powerlines (right), at 20m (top)

Test Environments



Ames NUARC Facility

Ames Roverscape

Ames DART Facility

Stall Recovery Guidance

NASA-DLR meeting on Unmanned Aircraft research topics

Stefan Schuet, John Kaneshige, Thomas Lombaerts,
Kimberlee Shish, Vahram Stepanyan, Gordon Hardy,
Peter Robinson

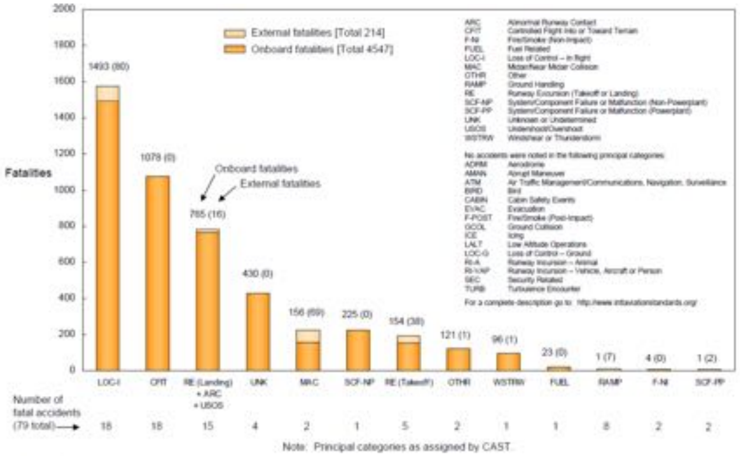
NASA Ames Research Center, Moffett Field

Structure

- Introduction
- Guidance strategies
- Display
- Simulation results
- Two implementation stages

Introduction

- Loss of control in flight remains the most frequent primary cause of accidents
- Stall related accidents: Colgan Air 3407, AirAsia 8501, XL Airways Germany 888T, Air Algerie 5017, Air France AF447,…



Note: Principal categories as assigned by CAST

CAST studies:

- **Effective Upset Prevention and Recovery Training**
- **Airplane State Awareness by aircrew (SE207)**
  - **Algorithms and display strategies to provide control guidance for recovery from approach-to-stall or stall**

Introduction

CAST The Commercial Aviation Safety Team

Research subtopics, based on CAST directives on safety enhancements:

order of priorities

1. **Upset prevention**
    - Adaptive safe flight envelope estimation
    - Autoflight trajectory prediction and alerting
    - Adaptive envelope protection

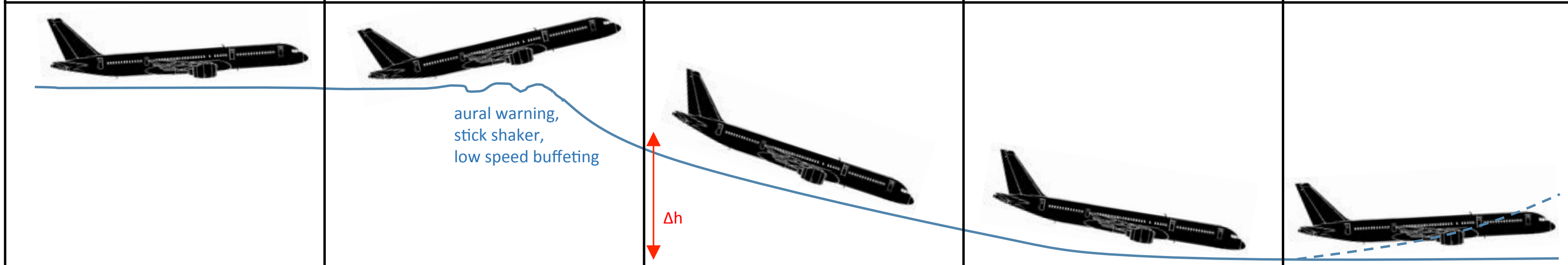
previous research (2012-2015)

2. **Upset recovery**
    1. Stall recovery guidance ← current research
    2. Unusual attitude recovery

Previous work published in the literature:

adaptive envelope estimation (AIAA-2013-4618/AIAA-2014-0268/AIAA-2015-1546) and protection (AIAA-2015-1113/AIAA-2016-0093)

Sequence of events for stall recovery



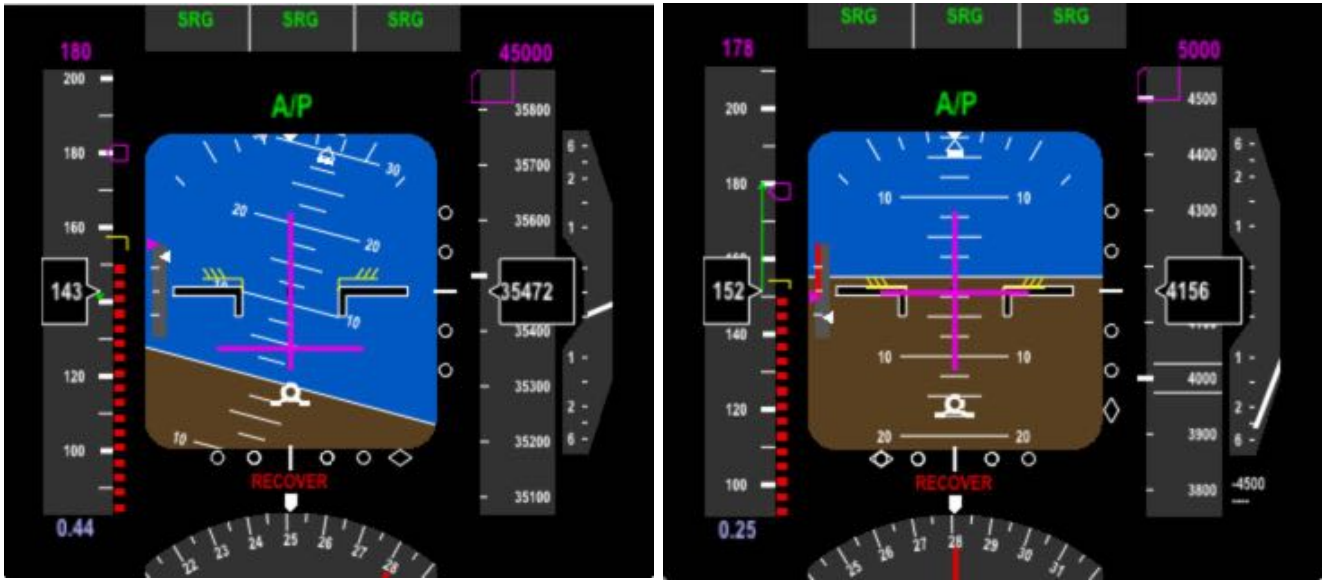
onset to stall	stall occurrence	stall recovery		
		accelerating dive	pitch up	out of stall
Decreasing airspeed, increasing angle of attack	Speed below stall speed, alpha exceeds stall value	Trade altitude for speed, potential → kinetic energy	Transition to level flight, avoiding secondary stalls or overstressing structure	Establish level flight or climb
FAA stall recovery template:	1. Disconnect autopilot and autothrottle/ autothrust	2. Nose down until stall indications eliminated, 3. Bank wings level, 4. Apply thrust as needed 5. Retract speed brakes and spoilers	6. Return to the desired flightpath	

Guidance strategies

3 strategies under consideration:

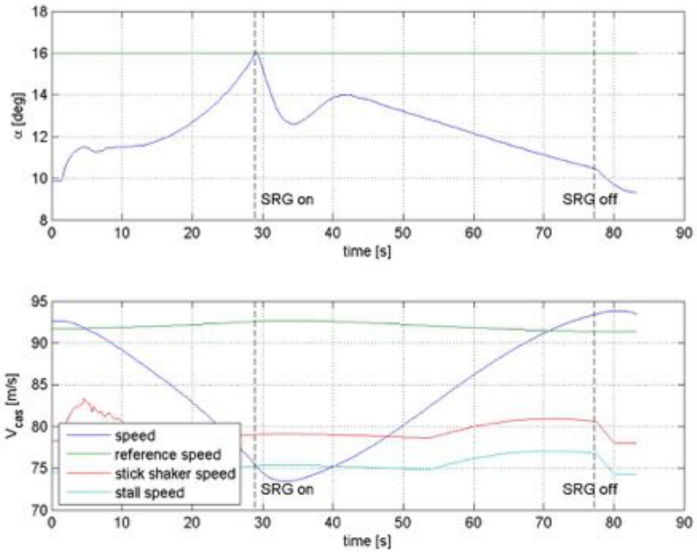
- Fast model predictive control (AIAA-2017-1513)
- Energy based guidance (AIAA-2017-1021)
- Constrained control approach (AIAA-2016-0878)

Display

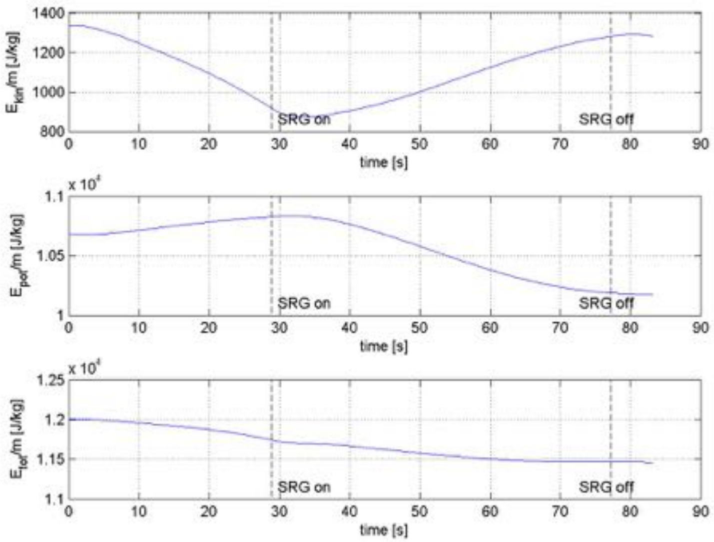


Simulation results

Angle of attack and calibrated airspeed



Energy transfers

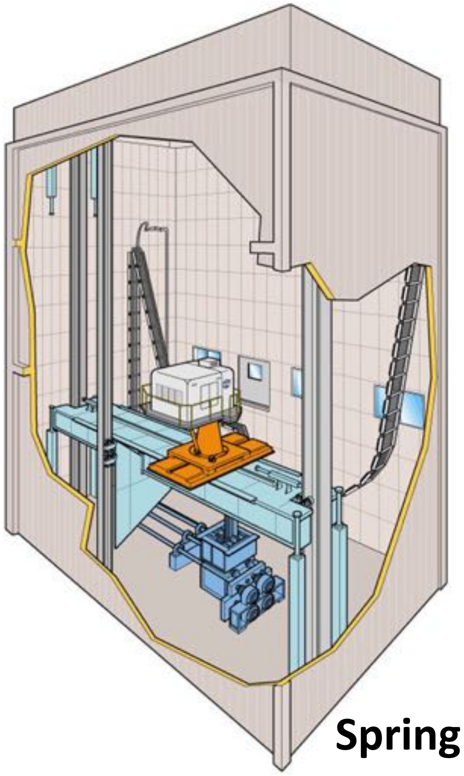


Two implementation stages

Advanced Controls Technologies (ACT) lab

Fall 2016

Vertical Motion Simulator (VMS)



Spring 2017

Intro – Guidance strategies – Display – Results – **Implementation**

Stall Recovery Guidance

NASA-DLR meeting on Unmanned Aircraft research topics

Stefan Schuet, John Kaneshige, Thomas Lombaerts,
Kimberlee Shish, Vahram Stepanyan, Gordon Hardy,
Peter Robinson

NASA Ames Research Center, Moffett Field

Flight Controls for Flexible Air Vehicles

Prepared by

Sean Swei and Kenneth Cheung

NASA Ames Research Center

in collaboration with

NASA, MIT, Michigan State U., UCSC, U. of Alabama

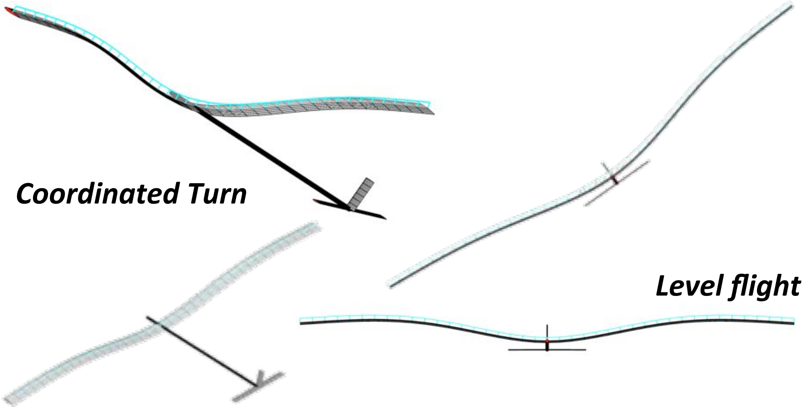
March 14, 2017

National Aeronautics and Space Administration

Outline

- ◆ Mission Adaptive Digital Aerostructure Technologies (MADCAT)
- ◆ Linear Parameter Varying (LPV) Modeling & Controls
  - ➢ Model Alignment
  - ➢ Adaptive Grid Step Size Determination

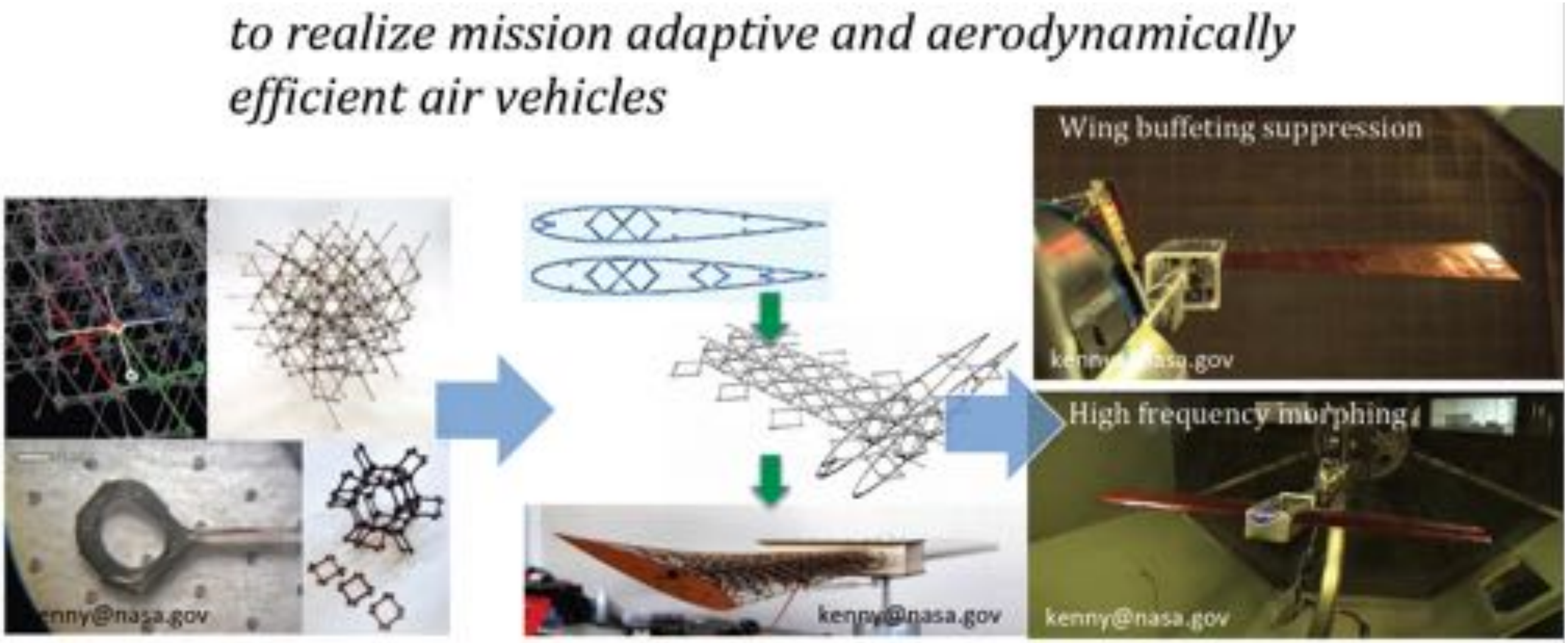
MADCAT v0



OPTIMAL WING SHAPING CONTROL

Mission Adaptive Digital Aerostructure Technologies (MADCAT)

- Develop a revolutionary aerostructure concept for future air vehicles by combining:
  - ➢ lattice-based discrete/digital construction approach
  - ➢ multi-objective optimal flight controls



to realize mission adaptive and aerodynamically efficient air vehicles

Component Development **Digital Construction** **Performance Assessment (wind tunnel tests)**

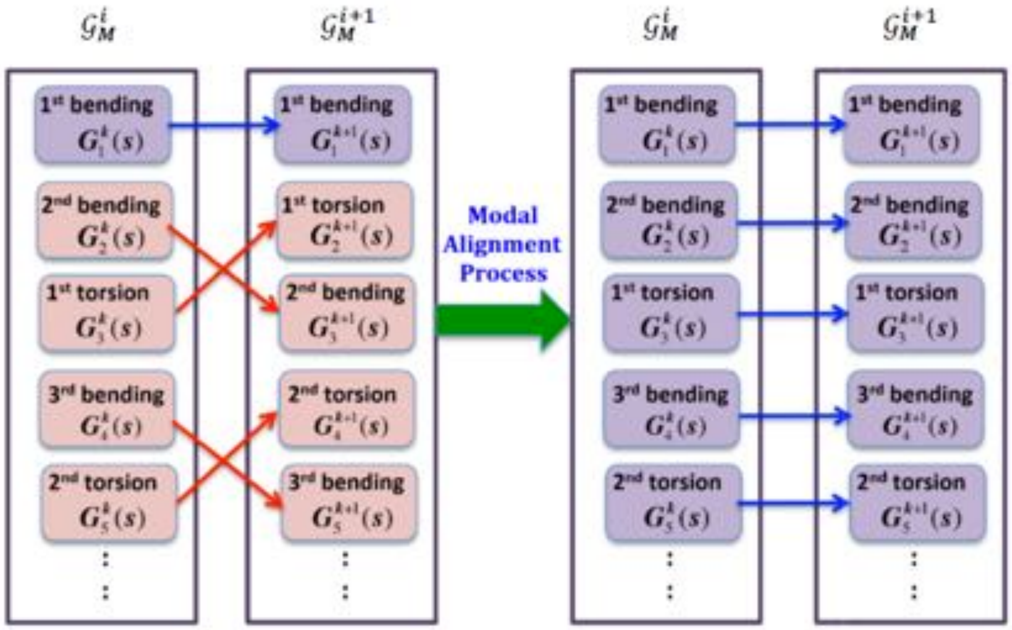
Mission Adaptive Digital Aerostructure Technologies (MADCAT)

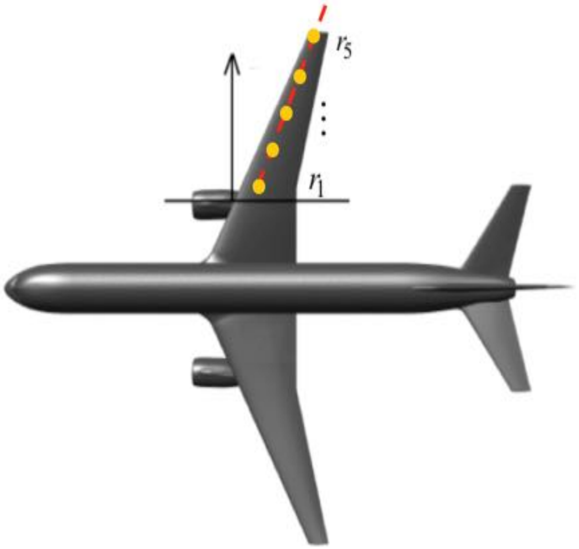
Performance Assessment: MADCAT v0 Flight Tests

N719NU

Linear Parameter Varying (LPV) Modeling

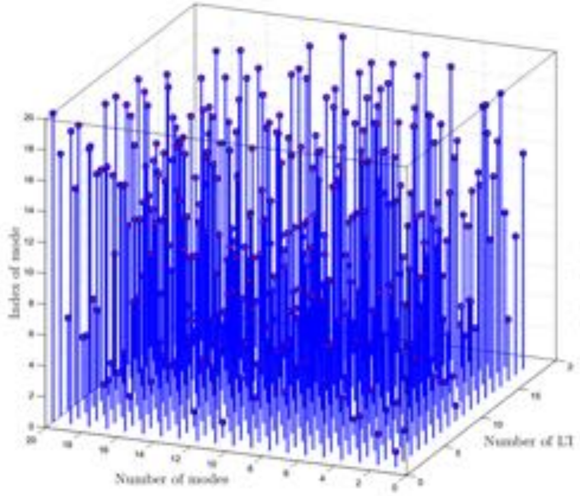
- **Flexible Model Alignment**



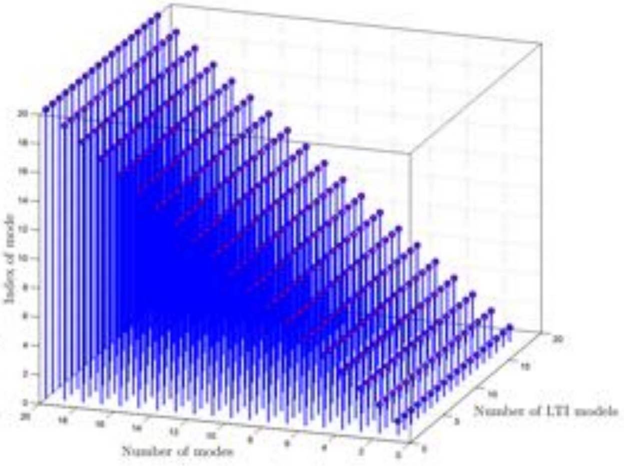


NASA Generic Transport Model (GTM)

Scrambled Mode #



Aligned Mode #

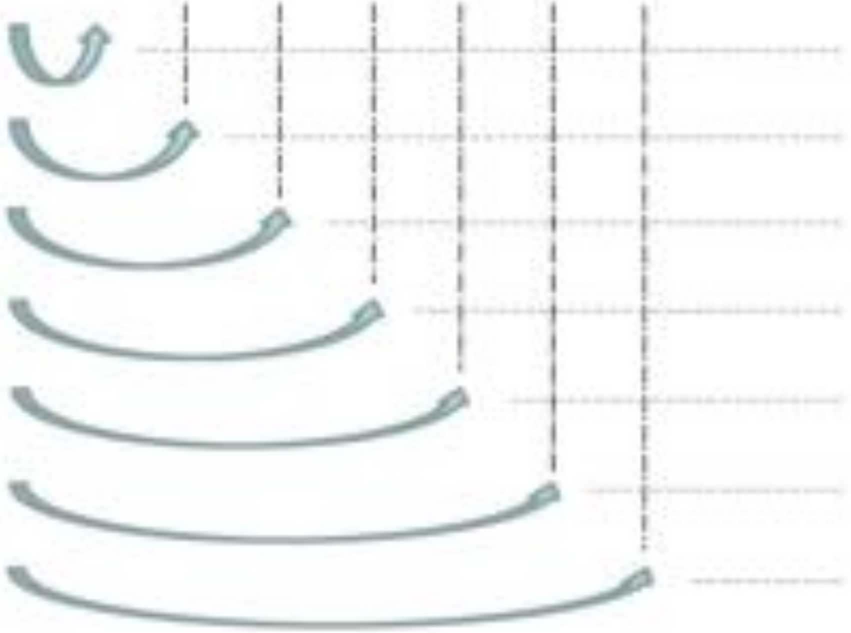


Linear Parameter Varying (LPV) Modeling

- **Adaptive Grid Step Size Determination**

18 aligned models at different Mach number

Local LTI Model	$\mathcal{G}^1$	$\mathcal{G}^2$	$\mathcal{G}^3$	$\mathcal{G}^4$	$\mathcal{G}^5$	$\mathcal{G}^6$	$\mathcal{G}^7$	$\mathcal{G}^8$	$\mathcal{G}^9$	$\mathcal{G}^{10}$	$\mathcal{G}^{11}$	$\mathcal{G}^{12}$	$\mathcal{G}^{13}$	$\mathcal{G}^{14}$	$\mathcal{G}^{15}$	$\mathcal{G}^{16}$	$\mathcal{G}^{17}$	$\mathcal{G}^{18}$
Mach Number	0.5	0.52	0.55	0.57	0.60	0.62	0.65	0.67	0.70	0.72	0.74	0.75	0.76	0.77	0.78	0.80	0.85	0.88



$\|\bar{\mathcal{G}}^{1,2}\|_{2-\sigma} < \delta$

$\|\bar{\mathcal{G}}^{1,3}\|_{2-\sigma} < \delta$

$\|\bar{\mathcal{G}}^{1,4}\|_{2-\sigma} < \delta$

$\|\bar{\mathcal{G}}^{1,5}\|_{2-\sigma} < \delta$

$\|\bar{\mathcal{G}}^{1,6}\|_{2-\sigma} < \delta$

$\|\bar{\mathcal{G}}^{1,7}\|_{2-\sigma} < \delta$

$\|\bar{\mathcal{G}}^{1,8}\|_{2-\sigma} > \delta$

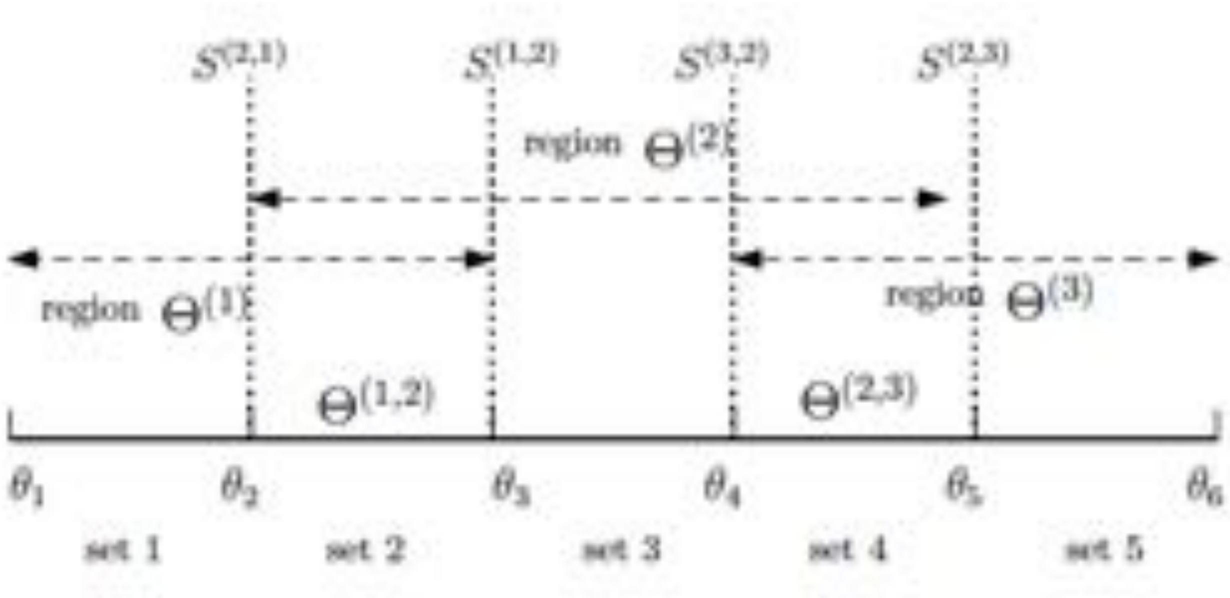
Delete models $\mathcal{G}^2$ to $\mathcal{G}^6$ and start next search based on $\mathcal{G}^7$

Note: σ-shifted $\mathcal{H}_2$-norm, denoted by $\mathcal{H}_{2\text{-}\sigma}$-norm, is defined by

$$\left\|G_j^i(s)\right\|_{2-\sigma}^2 = \left\|G_j^i(s+\sigma)\right\|_2^2$$

Switch LPV Controls

- **Sequential design of hysteresis switching LPV controllers**



Scheduling parameter division

Control Design Objectives:

Sequentially design a family of LPV controllers, such that: 1) the closed-loop systems are stable; 2) the controllers switch smoothly between neighboring controllers; 3) the flight performances are improved.

LMI Characterization

Thank You!

Sean Swei
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Thank You