Advanced Control and Autonomy Research

Dr. Nhan Nguyen

Technical Group Lead
Advanced Control and Evolvable Systems (ACES) Group
Intelligent Systems Division
NASA Ames Research Center
Moffett Field, CA

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**

**Intelligent Flight Planning**

**UAS Decision-Making**
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

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

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

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

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

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

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

Aeroservoelasticity (ASE) Modeling

X-56A Collaboration with NASA AFRC
**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

<table>
<thead>
<tr>
<th>NASA UAS Classification Matrix*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Category</td>
</tr>
<tr>
<td>Weight Limit</td>
</tr>
<tr>
<td>Airspeed Limit</td>
</tr>
</tbody>
</table>

* 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 be 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.

Detect, Operate-Near, and Avoid-Endangering Other Aircraft

Detect, Operate-Near, Avoid-Endangering Other Aircraft

Detect, Operate-Near, and Avoid-Endangering DGOs

Detect, Operate-Near, and Avoid-Endangering SGOs

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

2. GPS Denied/Degraded

3. Static/Dynamic Obstacles
UrbanScape Wind Uncertainties

Urban Architecture and CFD Simulation of Wind Profiles.
UrbanScape Wind Uncertainties
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
- Roverscape
- Ames DART Facility
- Ames NUARC Facility

21
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,…

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

Intro – Guidance strategies – Display – Results – Implementation
Introduction

Research subtopics, based on CAST directives on safety enhancements:

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

2. **Upset recovery**
   1. Stall recovery guidance
   2. Unusual attitude recovery

Previous work published in the literature:

# Sequence of events for stall recovery

<table>
<thead>
<tr>
<th>Onset to Stall</th>
<th>Stall Occurrence</th>
<th>Stall Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decreasing airspeed, increasing angle of attack</td>
<td>Speed below stall speed, alpha exceeds stall value</td>
<td>Accelerating dive</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pitch up</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Out of stall</td>
</tr>
</tbody>
</table>

### 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

Intro – Guidance strategies – Display – Results – Implementation
Two implementation stages

Advanced Controls Technologies (ACT) lab

Vertical Motion Simulator (VMS)

Fall 2016

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
Milestones

1. Complete an initial multi-objective optimization study with aeroelastic finite-element wing model coupled with longitudinal flight dynamic model, and subject to appropriate constraints.

2. Complete an initial robust control and distributed parameter control system design for coupled aircraft dynamics with aeroelastic wing structures to suppress fluttering motion.

Milestones:
Aeroelastic Stability Augmentation/Flutter Suppression Control
Outline

◆ Mission Adaptive Digital Aerostructure Technologies (MADCAT)

◆ Linear Parameter Varying (LPV) Modeling & Controls
  ➢ Model Alignment
  ➢ Adaptive Grid Step Size Determination

MADCAT v0

N719NU

kenny@nasa.gov

Coordinated Turn

Level flight

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)**
Linear Parameter Varying (LPV) Modeling

- Adaptive Grid Step Size Determination

### Note:

$\sigma$-shifted $H_2$-norm, denoted by $H_{2-\sigma}$-norm, is defined by

$$\left\| G_j^i(s) \right\|_{2-\sigma}^2 = \left\| G_j^i(s + \sigma) \right\|_2^2$$
Sequential design of hysteresis switching LPV controllers

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
Switching LPV Controls

Sequential hysteresis switching LPV controllers

Scheduling parameter division

Control Objective:

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 performances are improved.

LMI Characterization

Thank You!

Sean Swei
sean.s.swei@nasa.gov
650-604-0314
Thank You