Networked Flight Simulation and Control Laboratory

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AE Day
April 9, 2021

UMBERTO SAETTI
Assistant Professor
Department of Aerospace Engineering

- **Introduction**
  - ❑Presenter’s Bio
  - ❑Background and Motivation
- **Laboratory Vision**
  - ❑Approach
  - ❑Equipment
  - ❑Simulation Models
  - ❑Configuration
- **Intended Research**
  - ❑Linearized Models and Control of Rotorcratf Noise
  - ❑Identification of Time-Periodic Aerospace Systems
  - ❑Neural ODEs
  - ❑Dynamics and Control of Flapping-Wing Flight
  - ❑Dynamics and Control of eVTOL Vehicles

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Presenter's Bio

Education

- **Penn State**
  - ❑ Ph.D., M.Sc. Aerospace Engineering (2019, 2016)
  - ❑ M.Sc. Electrical Engineering (2017)
- **Politecnico di Milano** (Italy)
  - ❑ B.Sc. Aerospace Engineering (2014)

Research Experience

- June 2021: Assistant Professor (**Auburn University**)
- 2019-Present: Postdoctoral Fellow (**Georgia Tech**)
- 2015-2019: Graduate Research Assistant (**Penn State**)
- 2018: Visiting Scholar (U.S. Army ADD, **NASA** Ames)

Research Field

- Flight Dynamics & Controls, System ID, Time-Periodic Systems
  - ❑ Rotorcraft (helicopters, eVTOLs, UAS)
  - ❑ Flapping-wing flight (insects/birds, flapping-wing MAVs)
  - ❑ Fixed-Wing Aircraft (flapping-tail concept aircraft)

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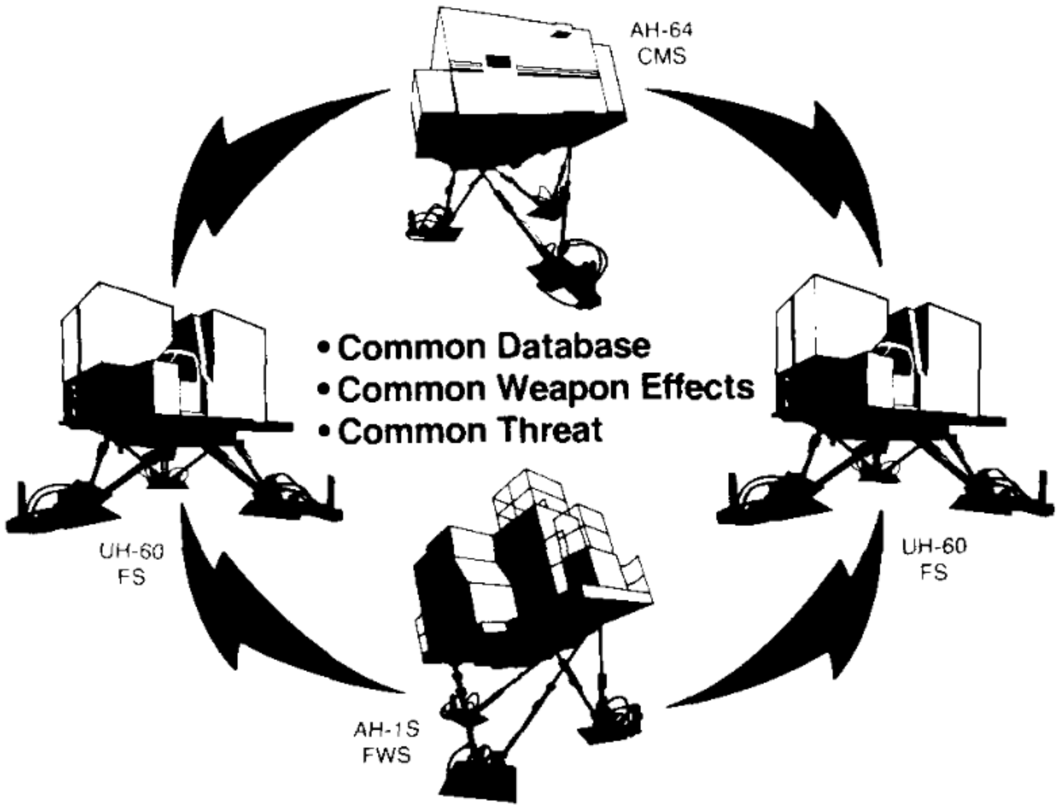
Background and Motivation

Background

- Simulation networking started in the 1980's
  - DARPA SimNet [Miller and Thorpe 1995]
  - MULTISIM [George et al. 1989]
- Used for mission rehearsal and team training in military operations
- Advantages
  - Linked simulators can be etherogeneous
  - Simulator need not being co-located
  - Simulation units can be added and removed → flexible
- Allows for multi-pilot/aircraft operations
  - Aerial refueling
  - Cooperative slung load
  - Air combat
  - Air traffic management
- Seldom used for research



Link Flight Simulation Division's Multiple Networking (MULTISIM) [George et al. 1989]

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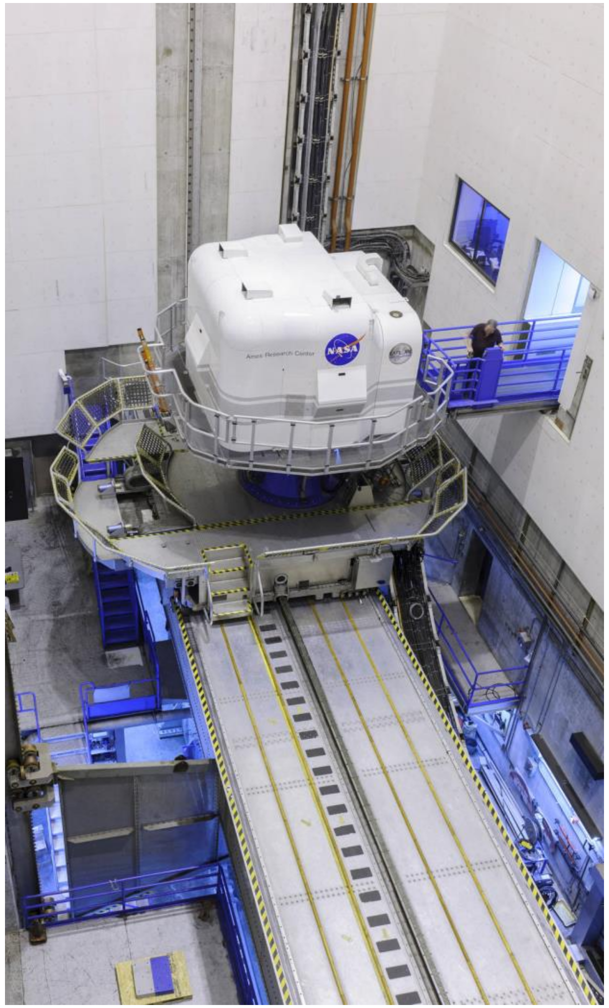
Background and Motivation

Motivation

- **Past approaches**
  - ❑ Projected screens + large motion bases
  - ❑ Realistic physical cockpits
  - ❑ High acquisition, maintenance, and operation cost
  - ❑ Typically government initiatives



Vertical Motion Simulator (NASA Ames)

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Background and Motivation

Motivation

- **Past approaches**
  - Projected screens + large motion bases
  - Realistic physical cockpits
  - High acquisition, maintenance, and operation cost
  - Typically government initiatives
- **Advent of Virtual Reality (VR)**
  - Eliminates need for large projected screens/physical cockpit
  - Reduces size and weight of motion platform
  - Lower mass/inertia → Increased motion bandwidth and range
  - Lower cost/size → Affordable for academic research
  - 360° visual environment

Brunner Elektronik NovaSim VR Simulator

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Approach (Cont'd)

VR/AR Headset

+

Haptic Feedback
Pilot Suit

+

Motion-Base
Simulator

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Approach (Cont'd)

Simulation Unit #1

Central Computing Unit

Simulation Unit #2

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Approach (Cont’d)

Multi-Purpose

- Can interface w/ MATLAB, Flightlab, Julia, etc.
- Can simulate different cockpit graphics

Reconfigurable

- Fixed-wing (GA + jet) + rotorcraft controls
- Can implement motion cueing algorithms

Modular

- Can link multiple units together

Enhanced Motion Cueing

- Low mass/inertia → Increased motion bandwidth and range

Immersive

- VR provides 360° visual environment
- Look-down capability
- Pilot can see its hands and interact with cockpit
- Haptic feedback (force-feel controls + suit + gloves)

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Approach (Cont'd)

Broad Research Topics

- Fundamental research on VR/AR
  - ❑ Piloted flight simulation
  - ❑ Handling qualities evaluation
- Development and testing of advanced flight control systems
- Novel cueing systems and algorithms
  - ❑ Tactile
  - ❑ Haptic (force-feel controls and/or suit)
- Multi-pilot/aircraft operations
  - ❑ Aerial refueling
  - ❑ Cooperative slung load
  - ❑ Air combat
  - ❑ Air traffic management
- Simulation of high-acceleration flight w/ low-acceleration motion feedback
- Human-machine interaction
- Development of pilot models

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Equipment (Cont'd)

Motion Base + VR/AR Headset

6-DoF Motion Platform

- Max payload: 660 lb (300 kg)
- Displacement and velocity
  - **Heave**: $\pm$185 mm, $\pm$600 mm/s
  - **Surge**: $\pm$240 mm, $\pm$600 mm/s
  - **Sway**: $\pm$240 mm, $\pm$600 mm/s
  - **Roll, Pitch, Yaw**: $\pm$30 deg, $\pm$120 deg/s

Visual System

- XTAL 8k
- Display
  - Resolution: 3840x2160 (4K) per eye
  - 180 deg field of view
  - Refresh rate: 75 hz @ 4K per eye
- Hand Tracking
  - Ultraleap Motion Rigel
  - 170 deg circular viewing angle
- Eye tracking @ 100 Hz

Motion-Base Flight Simulator

VR/AR Headset (XTAL 8K)

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Equipment (Cont'd)

Haptic Feedback Pilot Suit + Gloves

Pilot Suit

- Haptic system / NMES
  - ❑ 80 electrostimulation channels
  - ❑ 114 electrodes
- Biometry
  - ❑ Electrocardiography
- Motion tracking
  - IMU 9 axes and 6 axes modes
  - 10 internal motion capture sensors
- Connectivity
  - ❑ Wi-Fi 2.4 ghz

Haptic Gloves

- Sensoryx Haptic Gloves

TESLASUIT

Sensoryx Haptic Gloves

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Simulation Models

ROtorcraft Simulation Engine (ROSE)

- Versions available
  - julia
  - MATLAB
- Current Models
  - **Simple Helo** (UH-60, Bell 430)
  - **ARMCOP** (UH-60, AH-1, Bell 430)
  - **GenHel** (UH-60)
  - **GenHel** (UH-60) + **Free Wake**
- Other Models
  - **F-16**
  - **Aeroacoustics Solver** (Marching Cubes)
- Graphics
  - X-Plane

UH-60 Black Hawk

Bell 430

AH-1 Cobra

F-16 Fighting Falcon

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Configuration

Simulation Unit #1

Central Computing Unit

Simulation Unit #2

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Configuration (Cont’d)

Simulation Unit #1

Central Computing Unit

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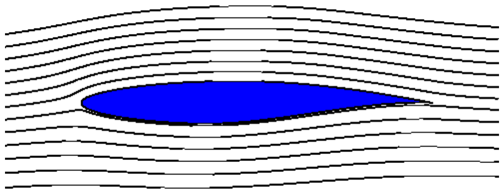
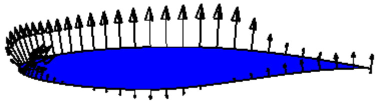
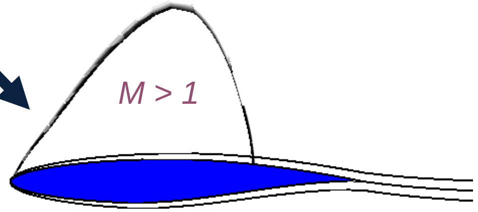
Linear Models and Control of Rotorcraft Noise

Ffowcs Williams-Hawkings Equation

$$\nabla^2 p'(\boldsymbol{x},t) = \frac{\partial}{\partial t}[Q\delta(f)] - \frac{\partial}{\partial x_i}[F_i\delta(f)] + \frac{\partial}{\partial x_i x_j}[T_{ij}H(f)]$$







Thickness
displacement of fluid generates sound

Loading
accelerating force distribution generates sound (includes **BVI noise**)

Quadrupole
All volume sources, non-linear effects nonuniform sound speed

Courtesy of K. S. Brentner

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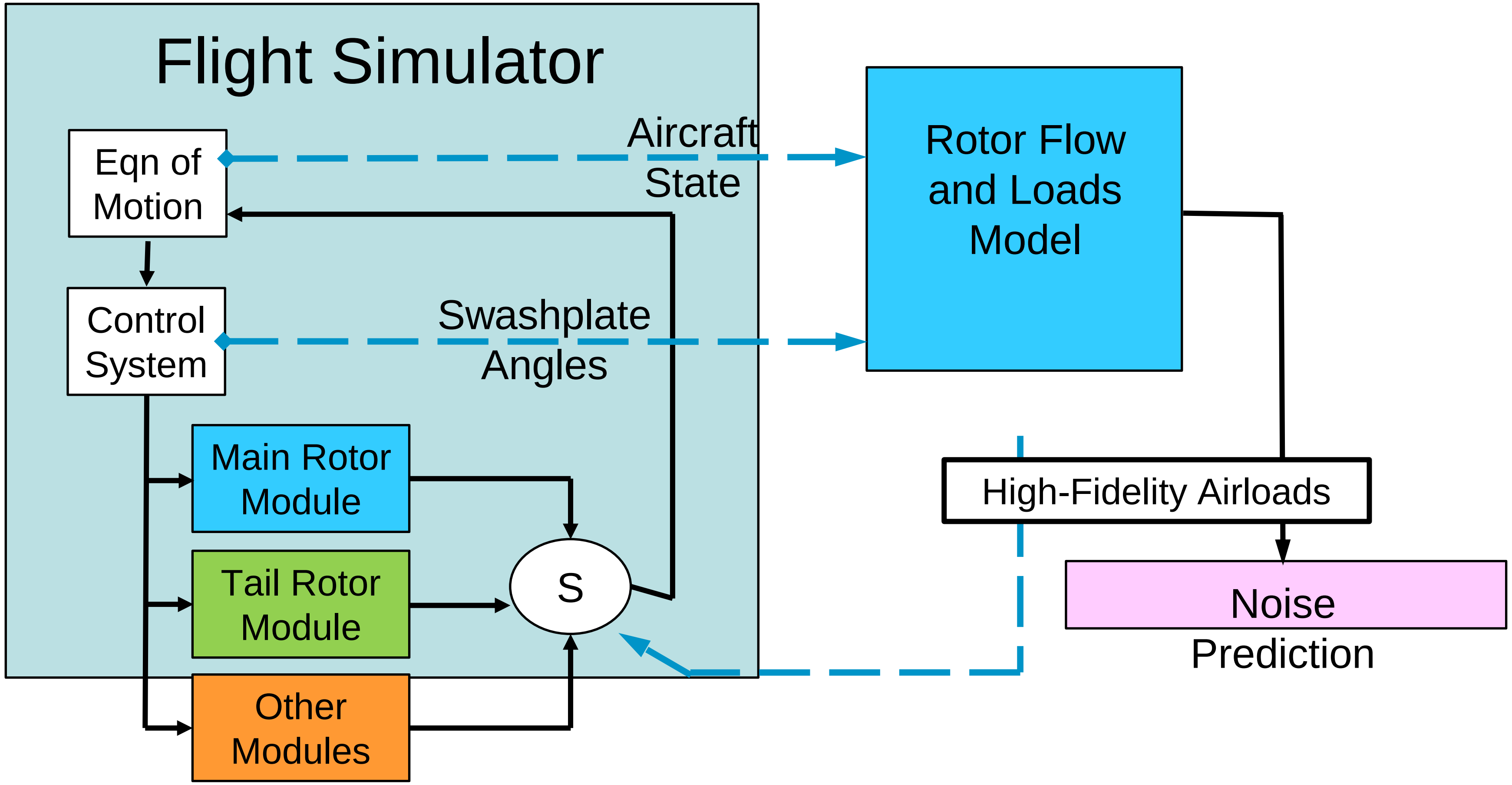
Linear Models and Control of Rotorcraft Noise



Courtesy of K. S. Brentner and M. Botre

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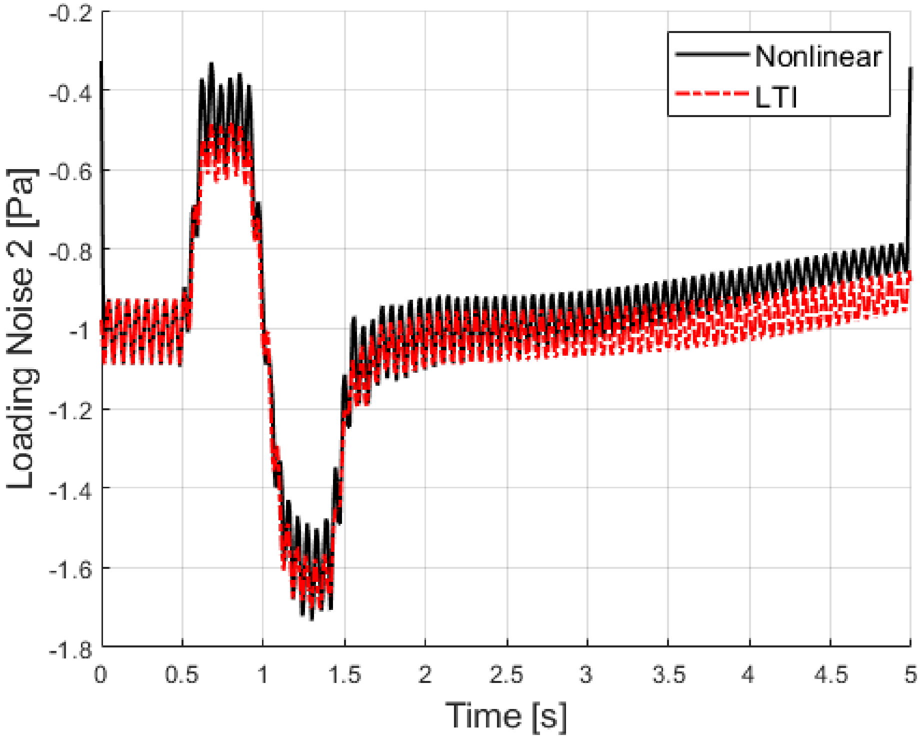
Linear Models and Control of Rotorcraft Noise

Ongoing Work

- Developed methodology to:
  - Include rotor noise as output of Non-Linear Time-Periodic (NLTP) system
  - Linearize coupled flight dynamics and acoustics
- Derive high-order LTI models for use in noise predictions

Future Research

- Real-time piloted simulations of coupled flight dynamics, free-wake, and acoustic
- Development of noise-abating flight control laws
  - Community noise (multiple rotorcraft)
  - Cabin noise
- Haptic cueing of noise



Nonlinear vs. LTI system for a longitudinal cyclic doublet

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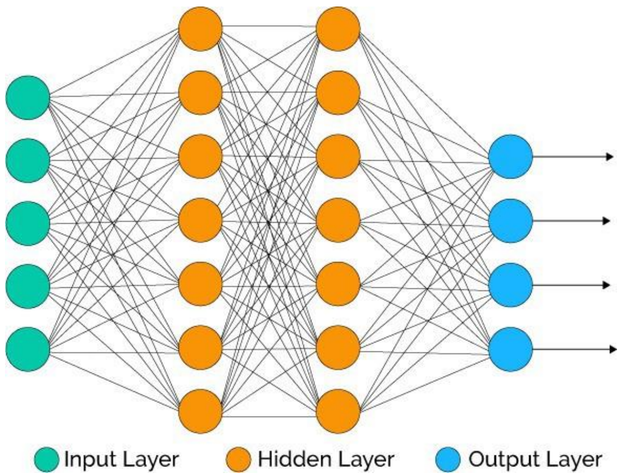
Neural ODE Applications to Aerospace Vehicles

Motivation

- Neural networks recently formulated as Ordinary Differential Equations (ODE's)
- Chen. R.T.Q., Y. Rubanova, J. Battencourt, D. Duvenaud, "***Neural Ordinary Differential Equations***", Neural INPS, 2018

Future Research

- Extend neural ODE's to aerospace vehicles applications
- Propose as an alternative to system ID
- Model matching with structured models
- Identification of linear systems



Neural Network

UH-60 Back Hawk

F-16 Fighting Falcon

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Identification of Linear Time-Periodic (LTP) Systems from Rotorcraft Flight Test Data

Motivation

- LTP identification for rotrcraft application in its infancy
- Current methods can only identify harmonics multiple of N_b/rev
- Subspace ID shows promise for LTP system ID

Objectives

- Extend subspace ID to rotorcraft applications
  - ❑ Simulation data
  - ❑ Flight-test data
- Control design based on flight-identified LTP systems
- Future Vercial Lift (FVL)

Sikorsky SB-1 Defiant (Army FVL)

Bell V-280 (Army FVL)

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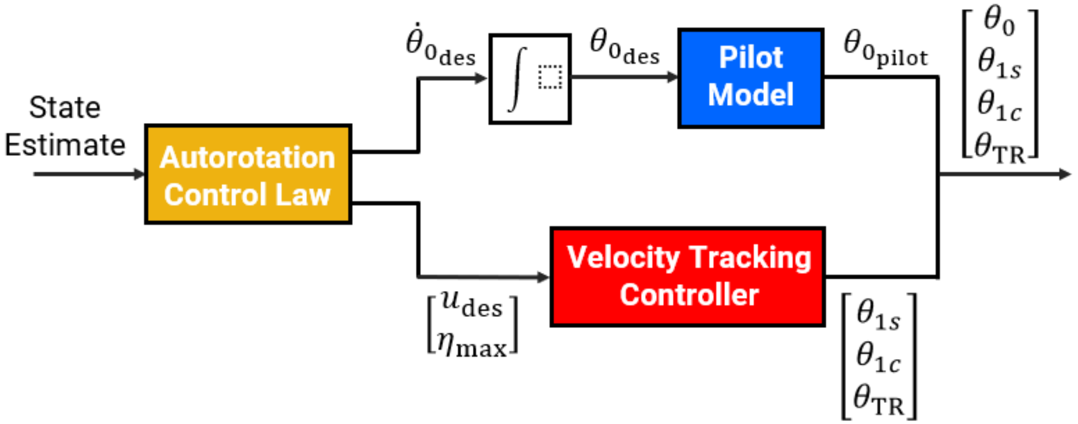
Control System Design for Pilot Cueing

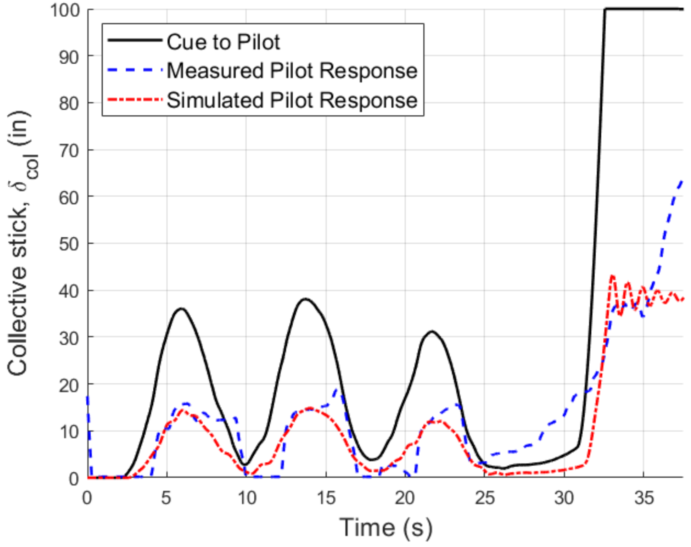
Motivation

- Pilot may not be able to track desired control inputs from control system
- Expert flight control system for autorotation is an example
- Need for control design that incorporates pilot dynamics

Objectives

- Develop control system design for cueing that account for pilot dynamics
- Study cueing methods for specific tasks
  - ❑ Autorotation
  - ❑ Shipboard landing
  - ❑ Carefree maneuvering
- Innovative cueing methods and test





Pilot model response to cues for safe autorotation

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Dynamics and Control of eVTOL Vehicles

Past Work

- Developed 6-DoF Simulation Models
- Propeller-driven rotor inflow model
- Assessed dynamic stability
- Flight Control Design
  - Explicit Model Following (EMF)
  - Dynamic Inversion (DI)
- Autorotation

Future Research

- Piloted flight simulations
- Handling qualities evaluations
- Assess aerodynamically-induced noise

Sponsor

- Vinati s.r.l.

F-Helix eVTOL Concept Aircraft (Legacy)

F-Helix eVTOL Concept Aircraft

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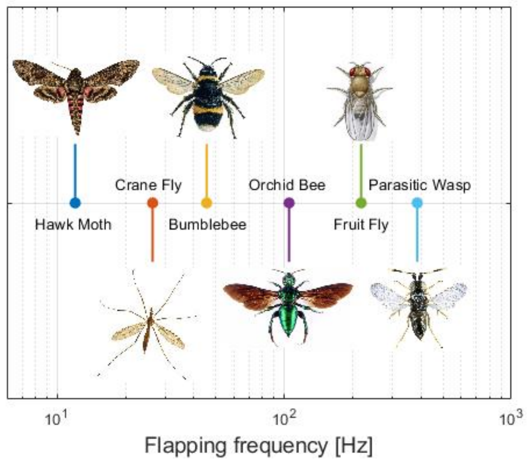
Stability Analysis and Control of Biological/Bio-inspired Flight

Motivation

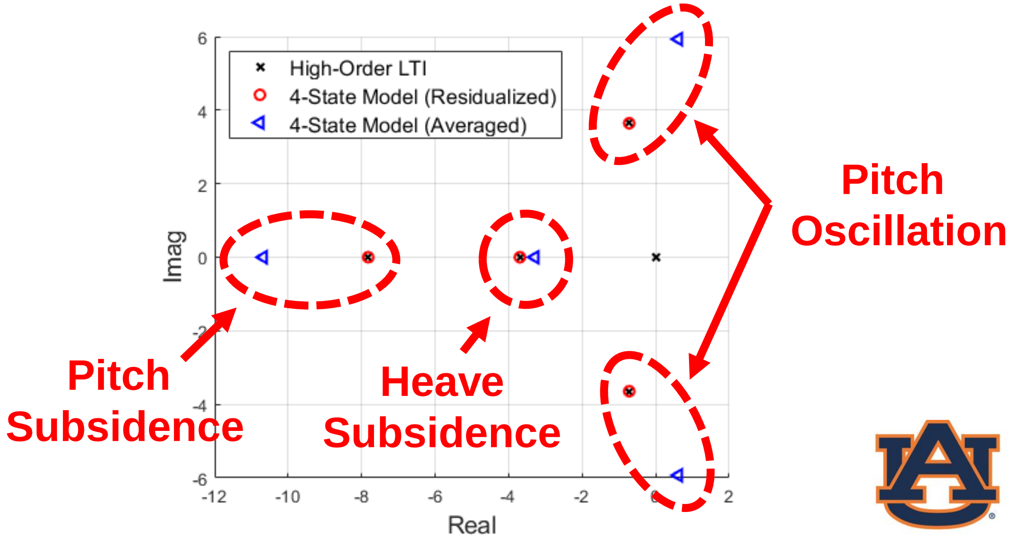
- No generalized method to describe the dynamics of flapping-wing flight
- Averaging methods need time-scale separation between
  - ❑ Forcing motion (flapping)
  - ❑ Fastest rigid-body mode

Objectives

- Extend harmonic decomposition methodology to flapping flight
- Analyze dynamic stability of wide spectrum of biological flyers
- Develop flight control laws that account for higher-order dynamics
- Demonstrate flight control laws in simulation and experimental studies



Flapping Frequency for Several Biological Flyers



NLTP vs LTI models

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Thank you

Questions?

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