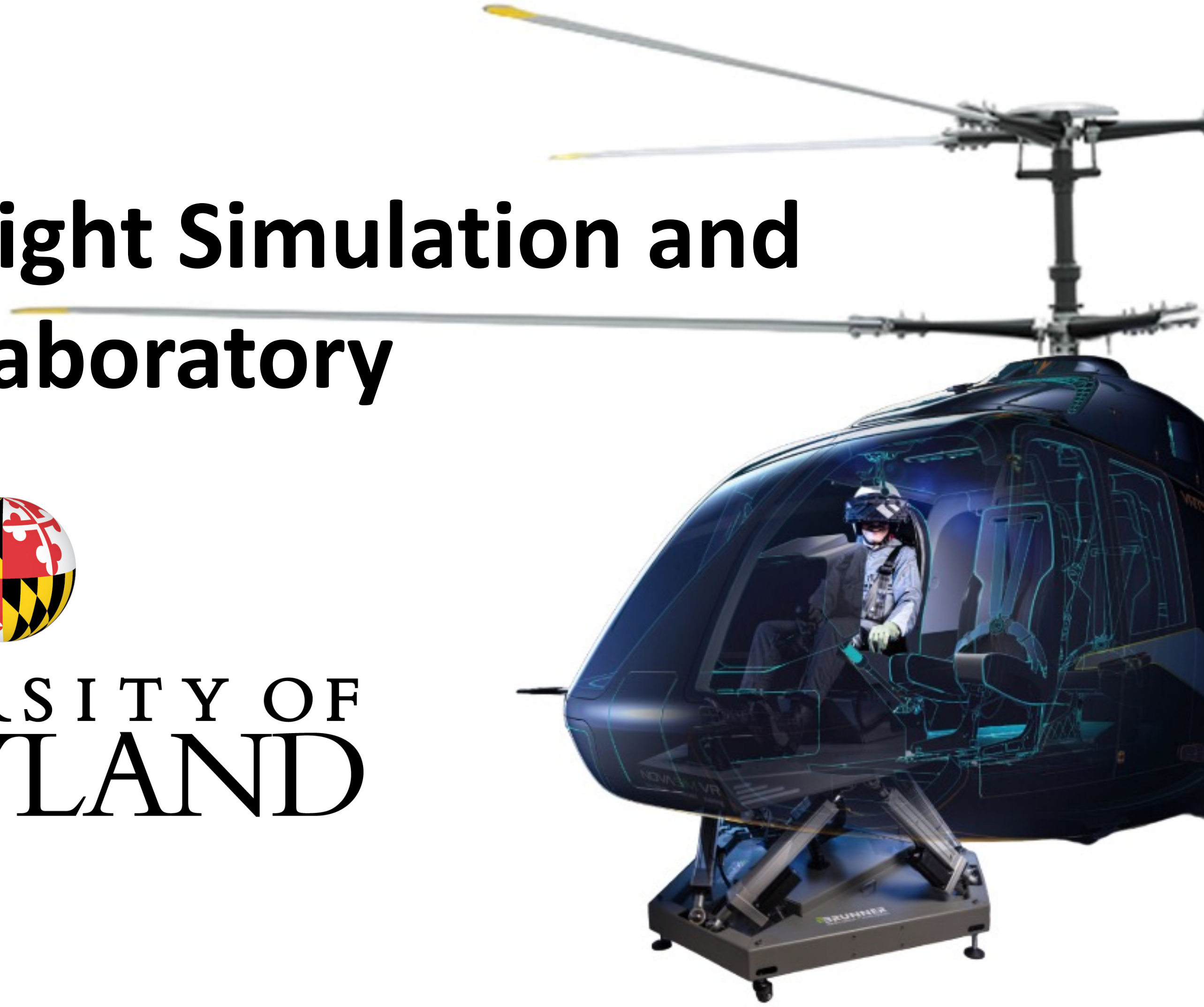
Extended Reality Flight Simulation and Control Laboratory



Dr. Umberto SAETTI
Assistant Professor
Department of Aerospace Engineering

- **Research Overview**
  - Bio
  - Overview of Research Topics
- **Experimental Capabilities**
  - Approach to Flight Simulation
  - Laboratory Setup
- **Computational Capabilities**
  - Simulation Models
  - Generic Multi-Rotor Flight Dynamics Model
  - State-Space Free-Vortex Wake
  - Aeroacoustic Solver
- **Sponsored Research Projects**

Principal Investigator Bio

Education

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

Research Experience

- Assistant Professor (**University of Maryland**) 2022-Present
- Assistant Professor (**Auburn University**) 2021-2022
- Postdoctoral Fellow (**Georgia Tech**) 2019-2021
- Graduate Research Assistant (**Penn State**) 2015-2019
- Visiting Scholar (U.S. Army ADD, **NASA** Ames) 2018

Research Field

- Flight Dynamics & Control, System ID, Handling Qualities
- Coupled Flight Dynamics, Aeromechanics, and Acoustics
- Time-Periodic Systems

Dr. Umberto Saetti

Assistant Professor
Department of Aerospace Engineering
3182 Glen L. Martin Hall
University of Maryland
Email: saetti@umd.edu
Web: umbertosaetti.com

Research Overview

Coupled Flight Dynamics, Aeromechanics, and Aeroacoustics Simulations

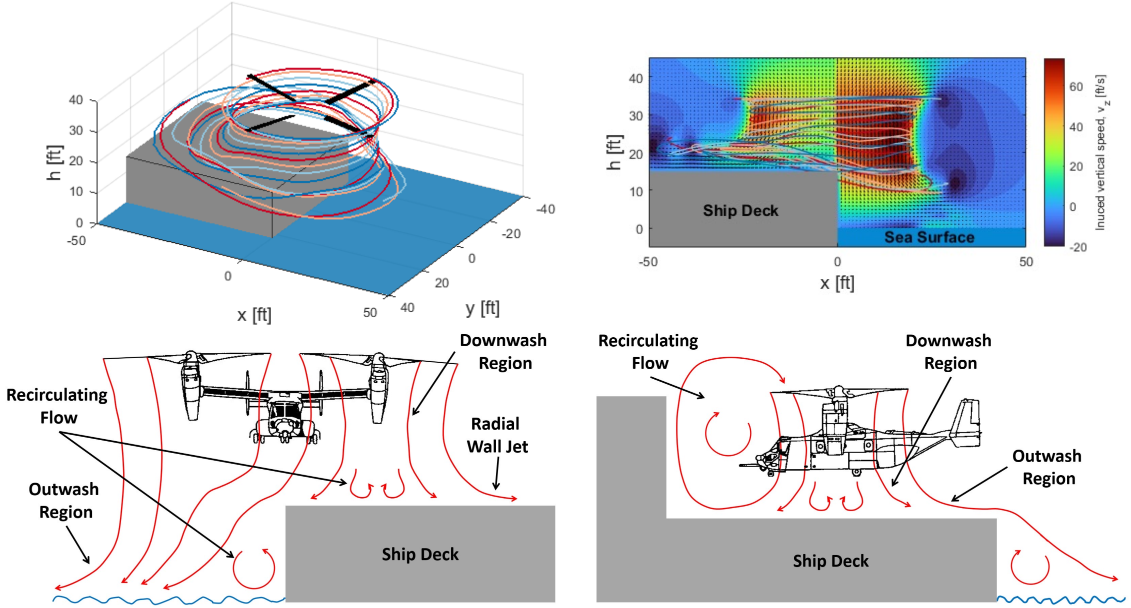
- Linearization, stability, order reduction, control
- Real-time aeromechanics and acoustics
- Real-time interactional aerodynamics
- Rotary-Wing Vehicles (helicopter, tiltrotors, etc.)
- Flapping-Wing MAVs (insects, birds)

Advanced Flight Control Systems

- Rotorcraft flight control systems
- Active noise-abatement flight control laws
- Active rotor vibration flight control laws

Perception Modeling and Pilot Cueing Methods

- Full-body haptic feedback
- Multimodal pilot modeling
- Cueing algorithms for autorotation/shipboard landing



Simulation and Control of Shipboard Interactions

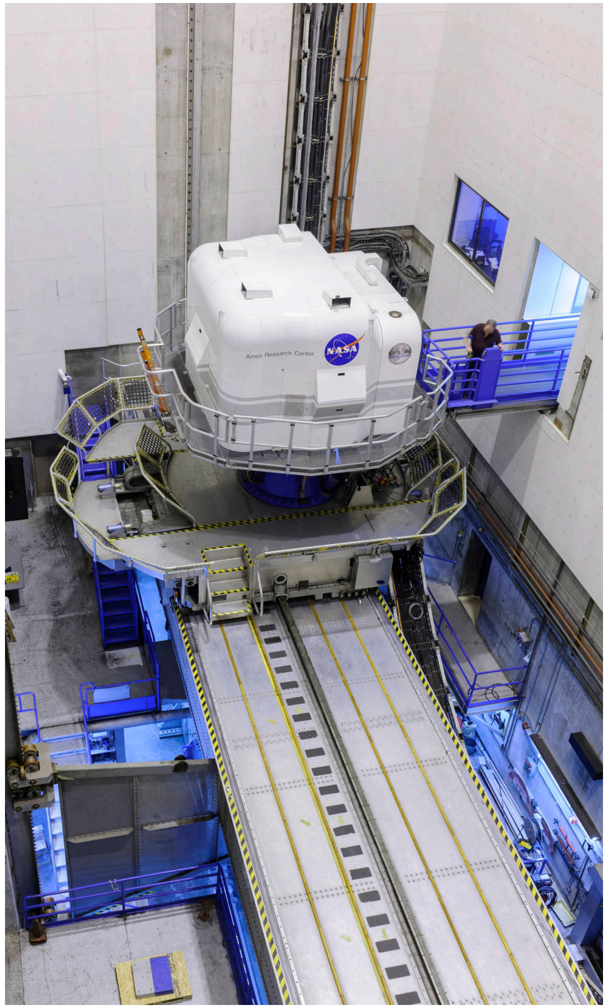
Haptic Feedback for Moon Landing

- **Research Overview**
  - Bio
  - Overview of Research Topics
- **Experimental Capabilities**
  - Approach to Flight Simulation
  - Laboratory Setup
- **Computational Capabilities**
  - Simulation Models
  - Generic Multi-Rotor Flight Dynamics Model
  - State-Space Free-Vortex Wake
  - Aeroacoustic Solver
- **Sponsored Research Projects**

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)

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

Extended Reality Flight Simulation and Control Lab

VR/AR Headset

- VRgineers XTAL 8K
- 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

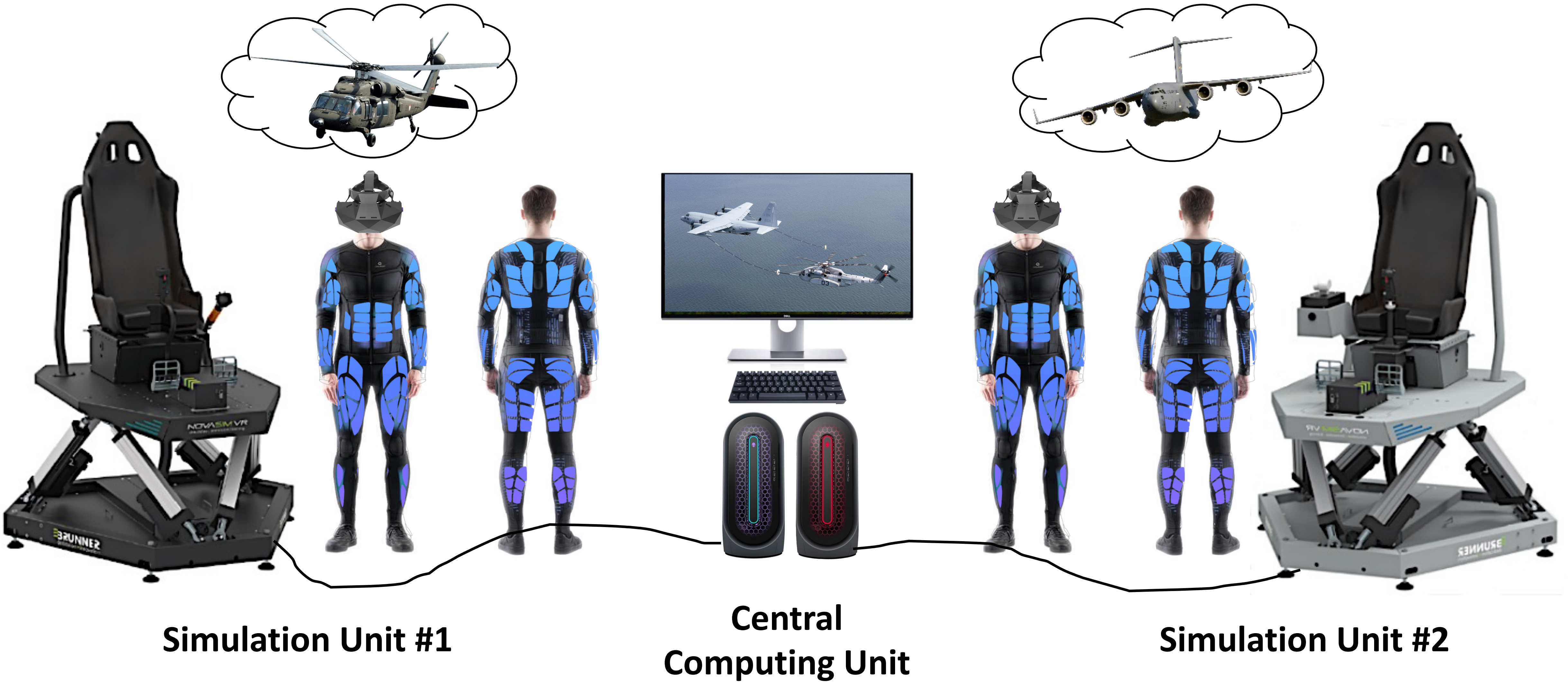
Full-Body Haptics

- TESLASUIT
- Haptic system
  - 80 electrostimulation channels (114 electrodes)
- Biometry (electrocardiography)
- Motion tracking
  - IMU 9 and 6 axes
  - 10 motion capture sensors

Motion-Base Simulator

- Max payload: 660 lb (300 kg)
- **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

Extended Reality Flight Simulation and Control Lab



Extended Reality Flight Simulation and Control Lab

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)

VR motion-base simulator at
Extended Reality Flight Simulation and Control Lab

Extended Reality Flight Simulation and Control Lab

- **Research Overview**
  - Bio
  - Overview of Research Topics
- **Experimental Capabilities**
  - Approach to Flight Simulation
  - Laboratory Setup
- **Computational Capabilities**
  - Simulation Models
  - Generic Multi-Rotor Flight Dynamics Model
  - State-Space Free-Vortex Wake
  - Aeroacoustic Solver
- **Sponsored Research Projects**

Flight Simulation Models

Versions Available

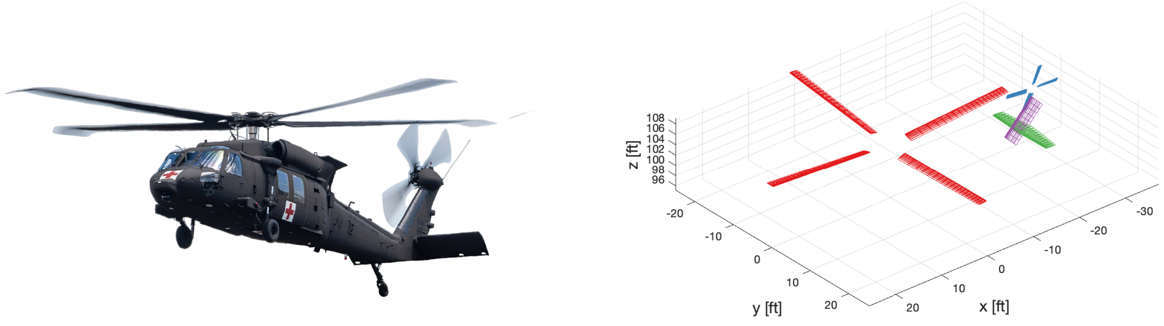
- ❑ MATLAB
- ❑ julia

Rotorcraft Models

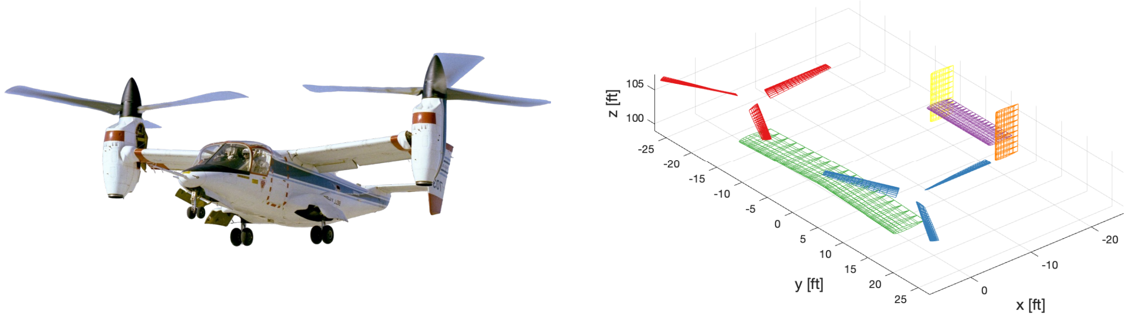
- ❑ **SimpleHel** (UH-60, AH-1, Bell 430)
  - Minimum fidelity
  - Quasi-static rotor dynamics
- ❑ **GenHel** (UH-60)
  - Higher fidelity
  - Rotor + inflow dynamics
- ❑ **GenTR** (XV-15, AW609)
  - Higher fidelity
  - Rotor + inflow dynamics
- ❑ **GenMR** (UAM/eVTOL, Co-Axial Rotorcraft)

Fixed-Wing Aircraft Models

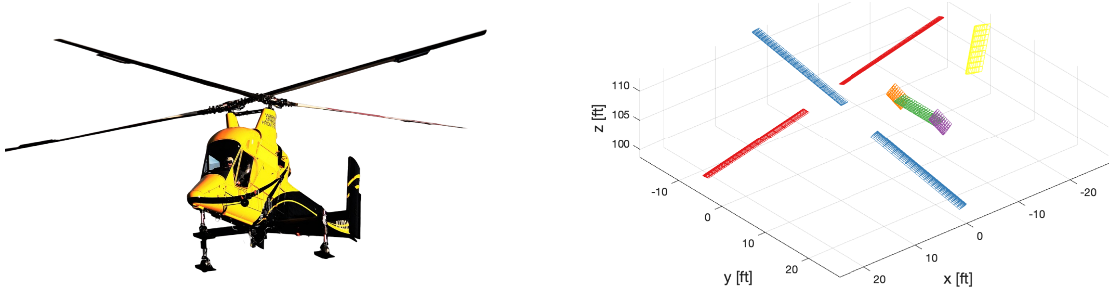
- ❑ F-16



UH-60 Black Hawk



Bell XV-15

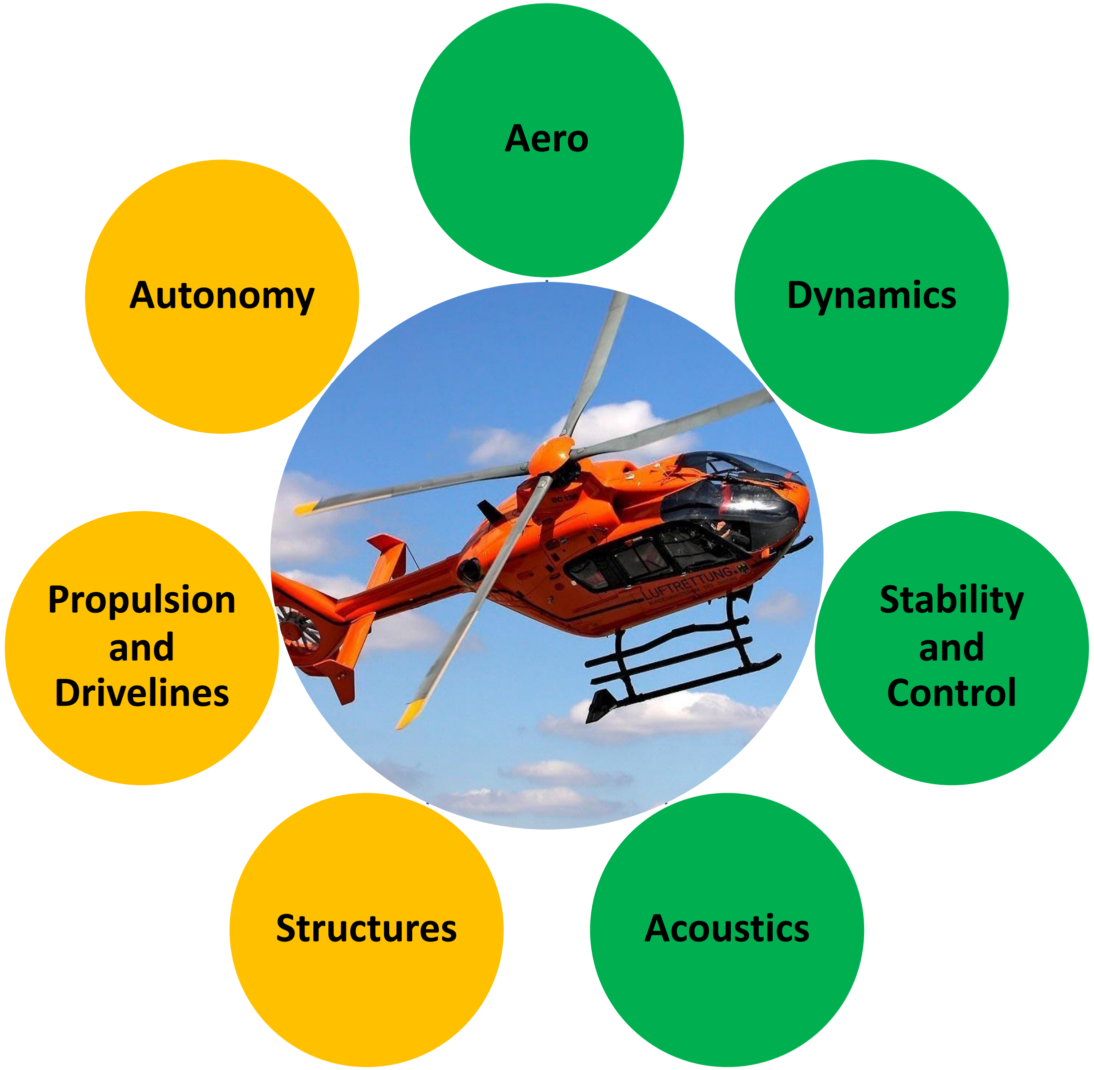


Kaman K-MAX

MATLAB Generic Multi-Rotor Flight Dynamics Simulator (M-GenMR)

Motivation

- New rotorcraft configurations more complex
  - ❑FVL and UAM
  - ❑Multiple rotors
  - ❑High-level of aero interaction
  - ❑High rotor RPM (UAV)
- Rapid prototyping of diverse configurations
  - ❑Multiple rotors
  - ❑Multiple wings
  - ❑Rotor-on-rotor/wing interactions
- Close gap
  - ❑Rotorcraft flight dynamics simulations
  - ❑Comprehensive aeromechanics codes
- Need for advanced flight control laws



MATLAB Generic Multi-Rotor Flight Dynamics Simulator (M-GenMR)

2021 — 2022 — 2023

M-GenHel

- MATLAB®
- Single main rotor config
- Rotor dynamics
  - Rigid flap + lead-lag
  - 3-state Pitt Peters (main rotor)
  - 1-state Bailey (tail rotor)
- Nonlinear aero
  - Airframe
  - Rotor blades

M-GenTR

- MATLAB®
- Tiltrotor config
- Rotor dynamics
  - Rigid flap + lead-lag
  - 3-state Pitt-Peters
- Nonlinear aero
  - Airframe
  - Rotor blades

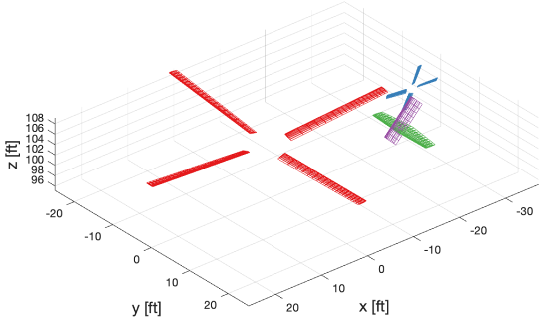
M-GenMR

- MATLAB®
- Generic multi-rotor/wing config
- Rotor dynamics
  - Rigid flap
  - 3-state Pitt-Peters
  - Rotor-on-rotor/wing interactions (CMTSVT)
- State-space free-vortex wake
- Built-in aeroacoustics solver
- Viz. of rotor/wing geometry

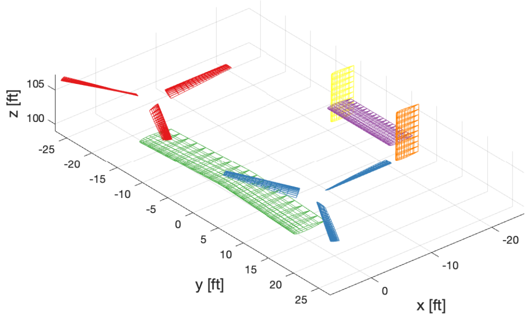
MATLAB Generic Multi-Rotor Flight Dynamics Simulator (M-GenMR)

Main Features

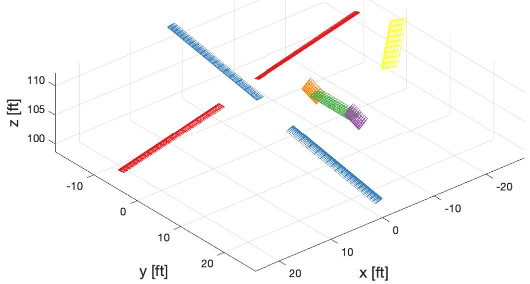
- ❑ Implemented in MATLAB
- ❑ Any number of rotors, wings, and blades
- ❑ Rotor dynamics
  - Rigid flap
  - 3-state Pitt-Peters
  - Rotor-on-rotor/wing interactions (CMTSVT)
- ❑ Wing aero
  - Lookup tables
  - Lifting line
- ❑ Aeromechanics/Aeroacoustics
  - State-space free-vortex wake
  - In-house aeroacoustics solver
- ❑ Linearization, trim, periodic trim routines
- ❑ Flight control laws
  - Dynamic Inversion (DI) auto-generated
  - Inner attitude + outer velocity loops
  - Redundant control allocation (pseudoinverse)

UH-60 Black Hawk

Bell XV-15

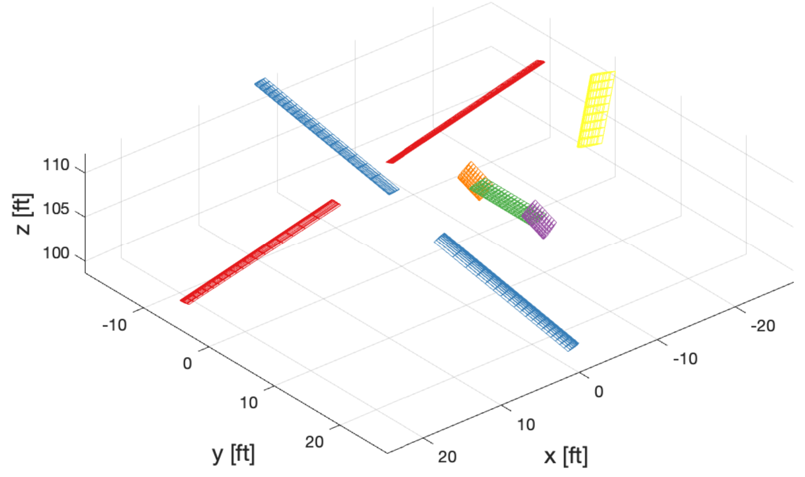



Kaman K-MAX

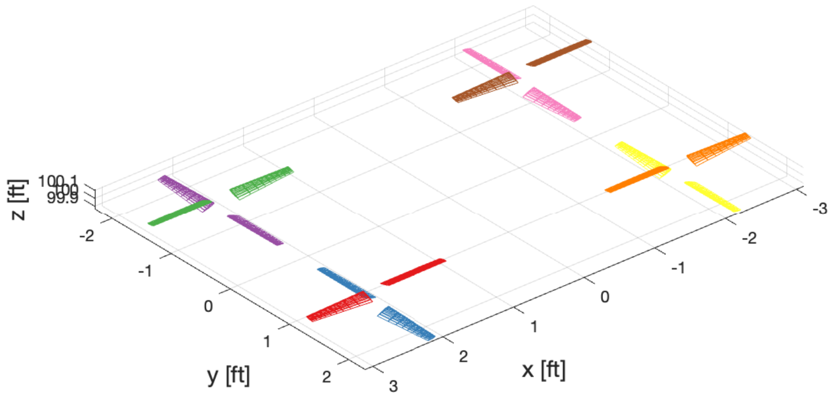
MATLAB Generic Multi-Rotor Flight Dynamics Simulator (M-GenMR)

Setup and Rotorcraft Geometry

- ❑ Any number of rotors/wings
    - Any number of blades (up to 9)
    - Can specify number of chordwise and spanwise elements
    - Arbitrarily oriented in space
- ❑ If data is available, setup of new rotorcraft takes ≈ 1 hour
- ❑ Setup via rotorcraft parameters script in MATLAB
- ❑ Can visualize rotor/blade geometry to check configuration



Kaman K-MAX

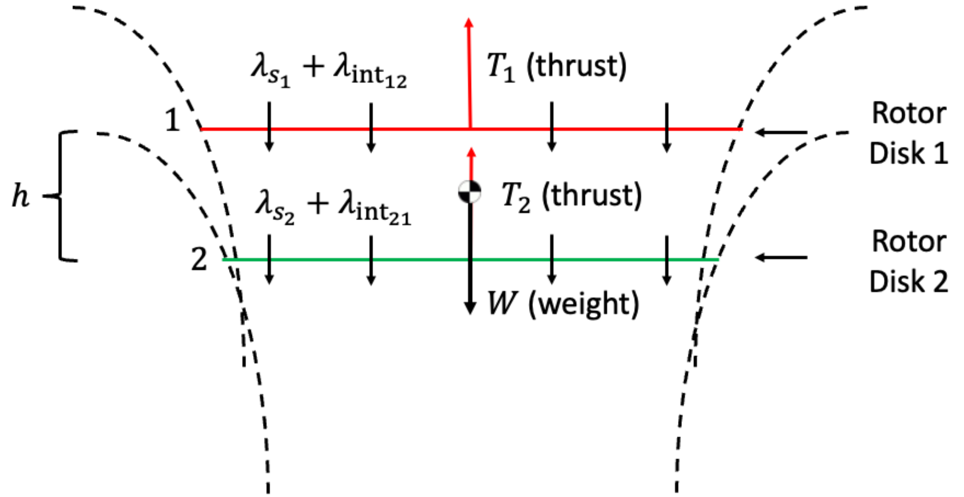


TRV-80

MATLAB Generic Multi-Rotor Flight Dynamics Simulator (M-GenMR)

Rotor Dynamics

- ❑ Blade-element model
- ❑ Rigid flap
- ❑ 3-state dynamic inflow (Pitt-Peters)
- ❑ Rotor-on-rotor interactions
  - State-space CMTSVT
  - Modification of Pitt-Peters matrices
  - Computer offline based on rotors geometry
- ❑ Rotor-on-wing interactions
  - Hyeson
  - Lifting line
- ❑ High-fidelity aeromechanics
  - State-space free-vortex wake
  - W/ and w/o near-wake vortex lattice model



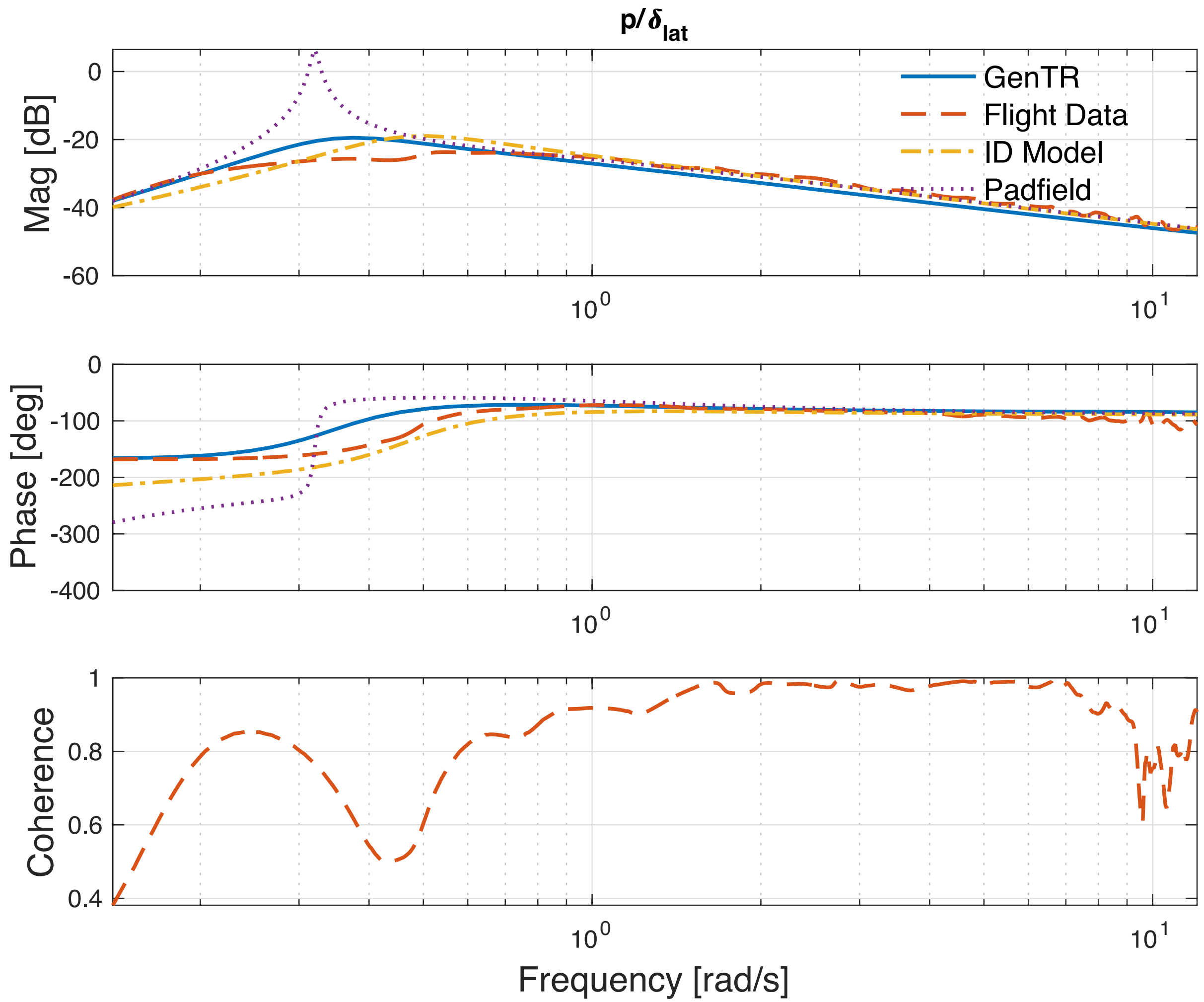
State-Space CMTSVT

- ❑ States: $\boldsymbol{x}^{\text{T}} = \{\boldsymbol{\lambda}_{\text{s}_1}^T \dots \boldsymbol{\lambda}_{\text{s}_n}^T \ \boldsymbol{\lambda}_{\text{tot}_1}^T \dots \boldsymbol{\lambda}_{\text{tot}_n}^T\}$
  - $\boldsymbol{\lambda}_{\text{s}_i}^T = \{\lambda_{s_{i0}} \lambda_{s_{i1c}} \lambda_{s_{i1s}}\}$: self-induced inflow on i^{th} rotor
  - $\boldsymbol{\lambda}_{\text{tot}_i}^T = \{\lambda_{\text{tot}_{i0}} \lambda_{\text{tot}_{i1c}} \lambda_{\text{tot}_{i1s}}\}$: total inflow on i^{th} rotor
- ❑ Self-induced inflow: $\boldsymbol{M}_{ii}\dot{\boldsymbol{\lambda}}_{s_i} = C - \boldsymbol{L}_{ii}^{-1}\boldsymbol{\lambda}_{s_i}$
  - $\boldsymbol{M}_{ii}, \boldsymbol{L}_{ii}$ same as Pitt-Peters
  - $\boldsymbol{F}_i^T = \{C_{T_i} C_{M_i} C_{L_i}\}$
- ❑ Total inflow: $\dot{\boldsymbol{\lambda}}_{\text{tot}_i} = \frac{1}{\tau_\lambda}(\hat{\boldsymbol{\lambda}}_{\text{tot}_i} - \boldsymbol{\lambda}_{\text{tot}_i})$
  - $\boldsymbol{\lambda}_{\text{tot}_i} = \boldsymbol{\lambda}_{s_i} + \sum_{j=1, j\neq i}^{n} \boldsymbol{\lambda}_{\text{int}_{ij}}$
- ❑ Interference inflow: $\boldsymbol{\lambda}_{\text{int}_{ij}} = L_{ij} e^{-\tau_{ij} s} \boldsymbol{\lambda}_{s_j}$

MATLAB Generic Multi-Rotor Flight Dynamics Simulator (M-GenMR)

Trim, Linearization, and Freq. Responses

- ❑ Linearization (perturbation methods)
- ❑ Averaged trim
- ❑ Periodic trim
  - Modified harmonic balance
  - Based on harmonic decomposition
- ❑ Model-order reduction
  - Residualization
  - Recovers 9-state rigid-body dynamics
  - Rotor states are assumed as fast decaying and residualized
- ❑ Freq. response
  - Possible to plot freq. responses
  - For given input-output pair
  - On- and off-axis



On-axis frequency-domain validation vs. flight test data for an XV-15

MATLAB Generic Multi-Rotor Flight Dynamics Simulator (M-GenMR)

Free-Vortex Wake (undergoing integration)

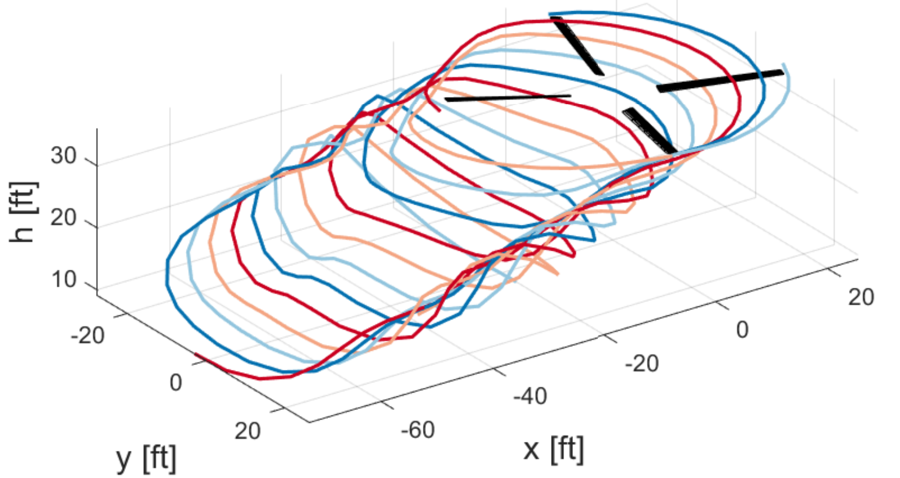
- Implemented in MATLAB
- State-variable implementation

$$\dot{\boldsymbol{r}}_{\mathrm{NW}} = -\Omega \boldsymbol{A}_\zeta \boldsymbol{r}_{\mathrm{NW}} + \boldsymbol{V}(\boldsymbol{r}_{\mathrm{NW}}(\phi,\zeta))$$
$$\dot{\boldsymbol{r}}_{\mathrm{TV}} = -\Omega \boldsymbol{A}_\zeta \boldsymbol{r}_{\mathrm{TV}} + \boldsymbol{V}(\boldsymbol{r}_{\mathrm{TV}}(\phi,\zeta))$$

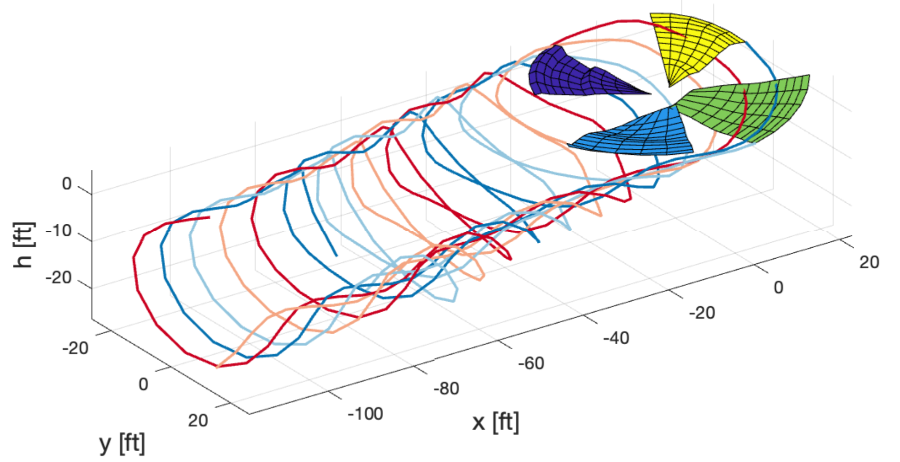
$$\dot{\Gamma}_{\mathrm{NW}} = -\Omega \boldsymbol{A}_\zeta \boldsymbol{\Gamma}_{\mathrm{NW}}$$
$$\dot{\Gamma}_{\mathrm{TV}} = -\Omega \boldsymbol{A}_\zeta \boldsymbol{\Gamma}_{\mathrm{TV}}$$

$$\dot{\boldsymbol{\Gamma}}_B = \frac{1}{\tau_{\Gamma_B}}\left[\boldsymbol{\Gamma}\left(\boldsymbol{r}_B(\phi,\zeta)\right) - \boldsymbol{\Gamma}_B\right]$$

- Can choose
  - Number of rotor wake revolutions
  - Time step
- Runs in real-time if autocoded to C/C++ via MATLAB/Simulink coder
- Can be run one- or two-way coupled



State-Space Free-Vortex Wake (tip vortex only)



State-Space Free-Vortex Wake (near wake model)

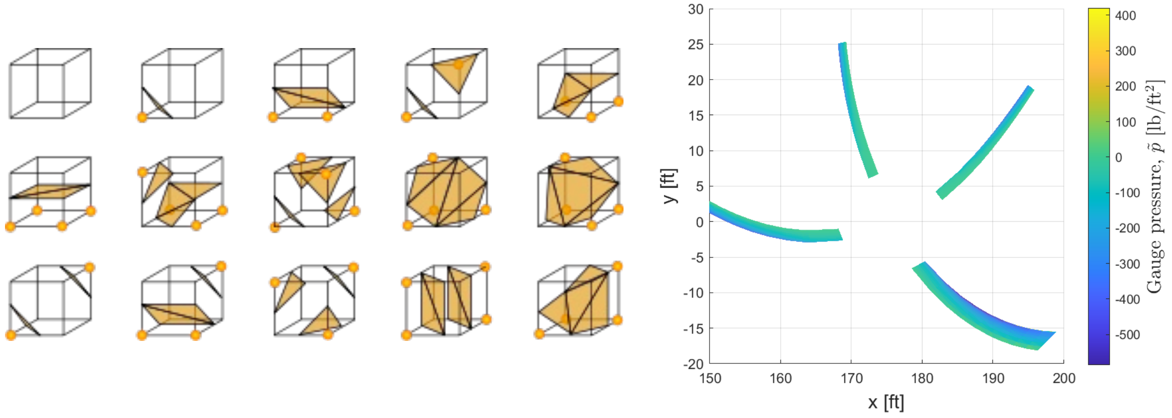
MATLAB Generic Multi-Rotor Flight Dynamics Simulator (M-GenMR)

Aeroacoustics Solver (undergoing integration)

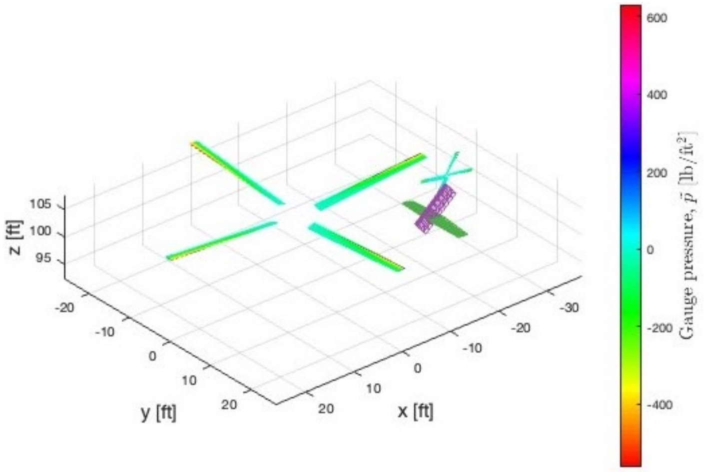
- ❑ Implemented in MATLAB
- ❑ Impermeable Ffowcs Williams-Hawkings surface formulation

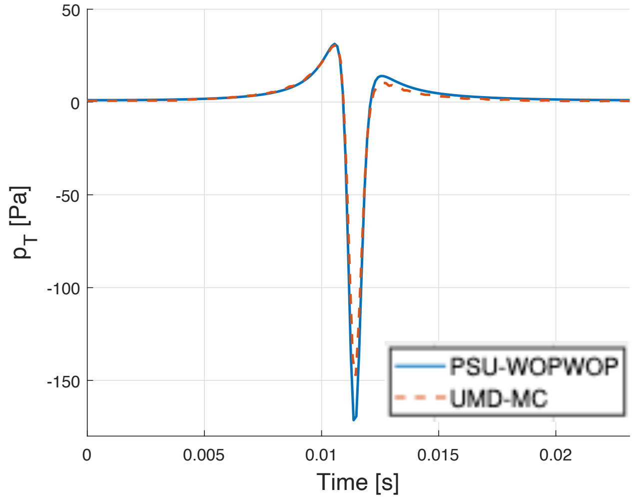
$$4\pi p'(x,t) = \frac{1}{c_0}\frac{\partial}{\partial t}\int_{\Sigma}\left[\frac{\rho_0 c_0 u_n + \tilde{p}\hat{\boldsymbol{n}}\cdot\hat{\boldsymbol{r}}}{r\Lambda}\right]_{\mathrm{ret}} d\Sigma + \int_{\Sigma}\left[\frac{\tilde{p}\hat{\boldsymbol{n}}\cdot\hat{\boldsymbol{r}}}{r^2\Lambda}\right]_{\mathrm{ret}} d\Sigma$$

- ❑ Marching-cubes algorithm to solve for iso-surface



Iso-surface computed with marching cubes approach



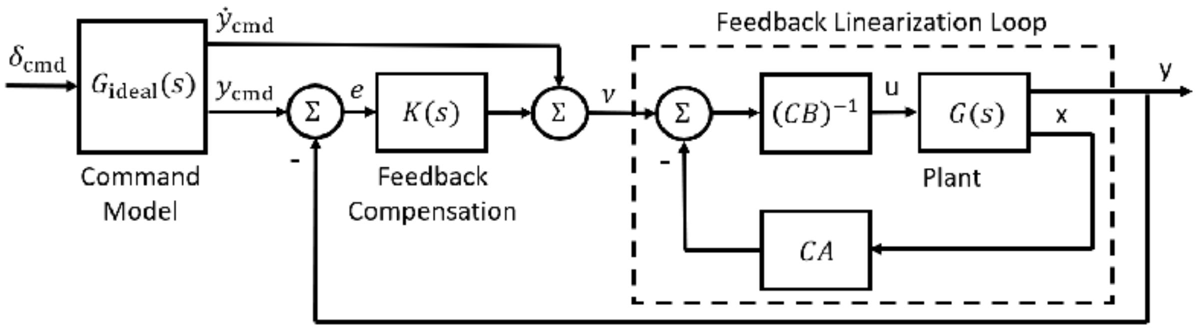


Acoustic pressure validation vs. PSU-WOPWOP

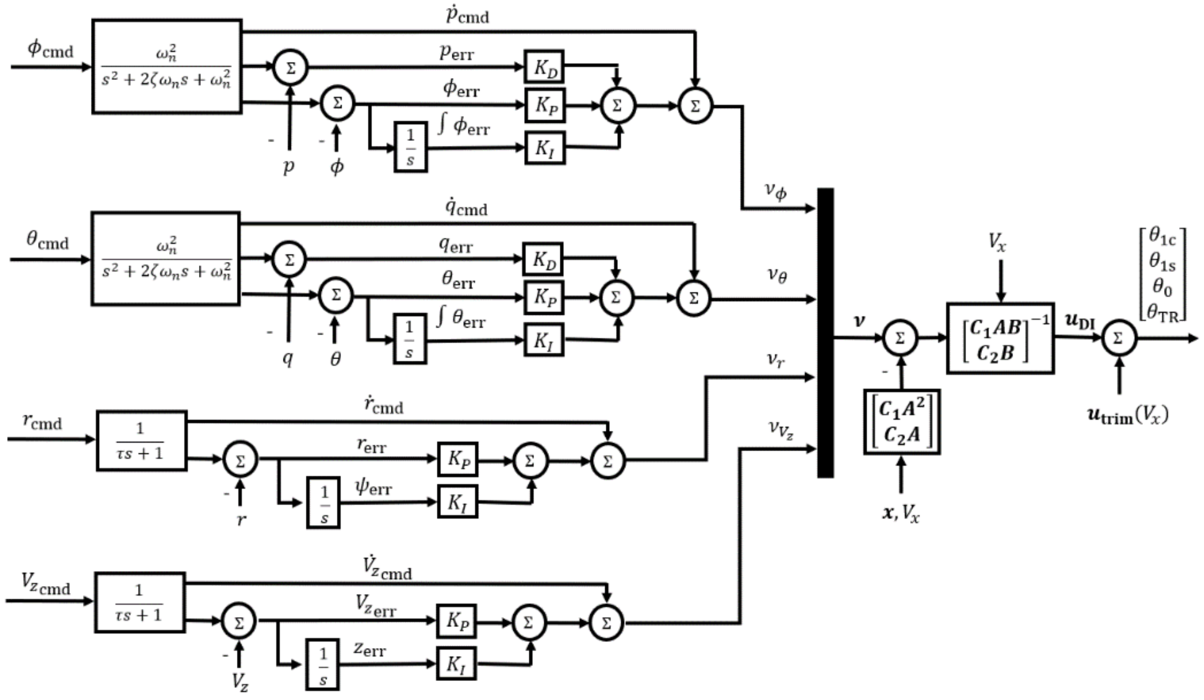
MATLAB Generic Multi-Rotor Flight Dynamics Simulator (M-GenMR)

Flight Control Laws

- ❑ Model-following control laws
- ❑ Implemented in Simulink
- ❑ Dynamic Inversion (DI)
  - Inner-attitude loop
  - Outer-velocity loop
  - Automatically generated across flight envelope → no need for gain scheduling
  - Scheduled with reduced-order linearized models
- ❑ Redundant control allocation
  - Pseudoinverse
  - Automatically generated based on active effectors
  - Based on linearized models



DI as applied to a SISO system



DI inner attitude loop

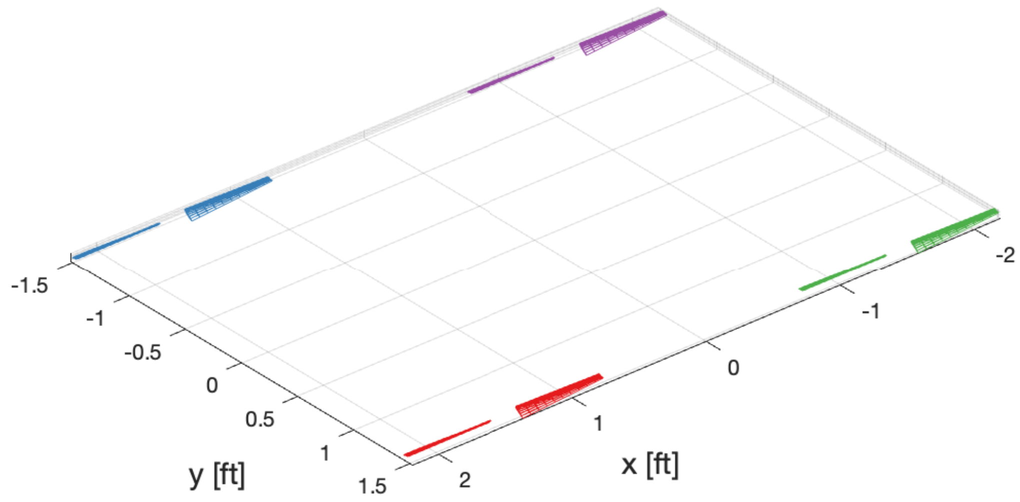
MATLAB Generic Multi-Rotor Flight Dynamics Simulator (M-GenMR)

Current Status

- ❑ Code validated vs. flight test data
  - UH-60
  - XV-15
- ❑ Currently validating vs. other flight test data
  - AW609 (Leonardo Helicopters)
  - Small-scale quad-, hexa-, and octo-copters (US Army CCDC)
  - TRV-80
- ❑ Currently validating
  - Rotor-on-rotor interactions
  - Rotor-on-wing interactions
- ❑ Still fixing a few minor bugs (is it ever over, anyways?)

Ongoing/Future Work

- ❑ Integration with state-space free-vortex wake
- ❑ Integration with aeroacoustic solver



US Army CCDC small-scale quadcopter configuration

- **Research Overview**
  - Bio
  - Overview of Research Topics
- **Experimental Capabilities**
  - Approach to Flight Simulation
  - Laboratory Setup
- **Computational Capabilities**
  - Simulation Models
  - Generic Multi-Rotor Flight Dynamics Model
  - State-Space Free-Vortex Wake
  - Aeroacoustic Solver
- **Sponsored Research Projects**

Linearized High-Fidelity Aeromechanics for Extended Reality Simulation and Control of Shipboard Interactions

Problem

- Rotor wake interaction w/ ship deck affects
  - Performance
  - Handling qualities
- Fatal MV-22 Osprey crashes (2015, 2017)

Solution

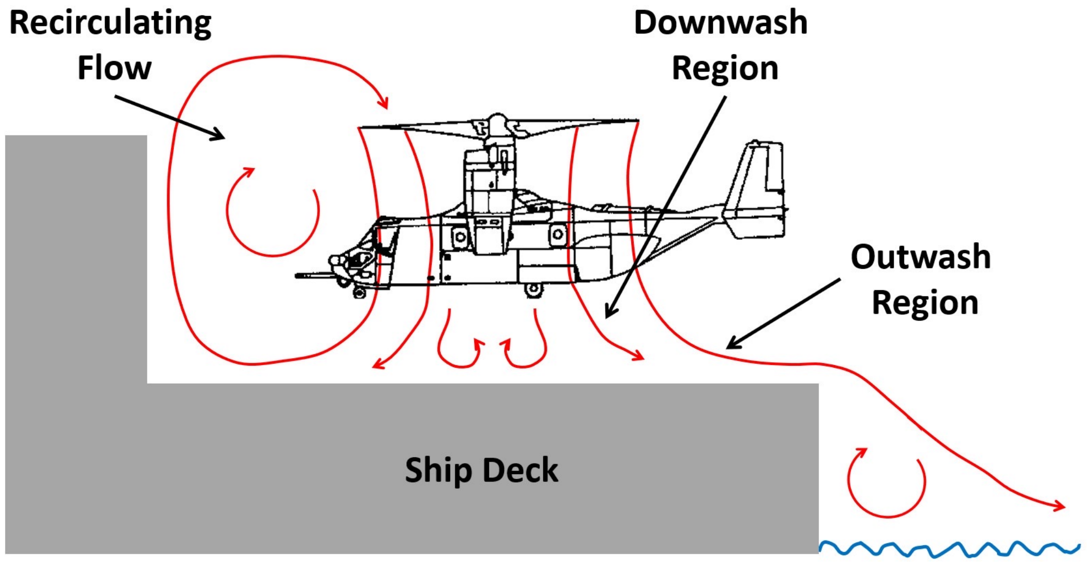
- Real-time prediction of adverse shipboard interactions
- Control laws to compensate for adverse interactions
- Innovative cueing methods (**full-body haptics**) for increased pilot awareness

Funding

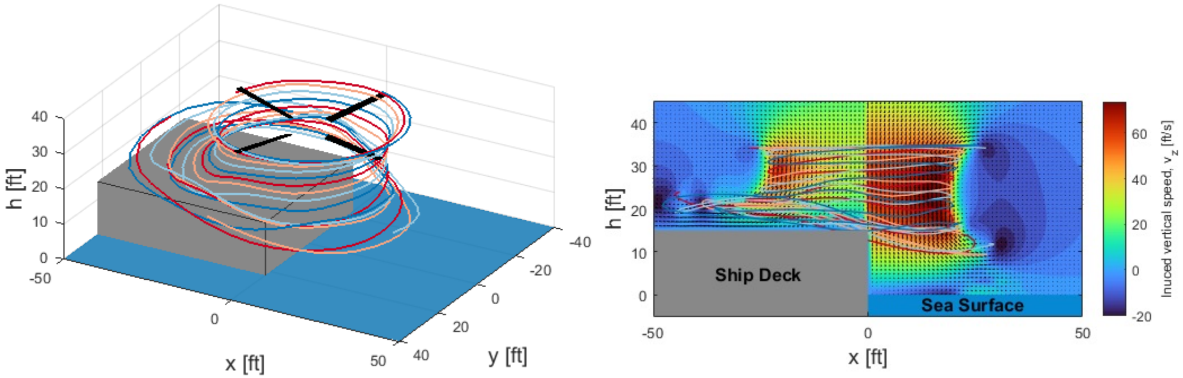
- **ONR YIP $ 510,000** (B. Holm-Hansen) – **Awarded**

Interactions

- John Tritschler (USNTPS)
- Sven Schmitz (Penn State)



Adverse shipboard interactions



State-space free-vortex wake for prediction of shipboard interactions

State-Space Implementation and Linearization of Simulations with High-Fidelity Aeromechanics

Problem

- Rotor noise expressed with PDE’s
  - ❑ Much slower than real-time
  - ❑ No linear model to base control system upon
- Complex to cue rotor noise visually

Solution

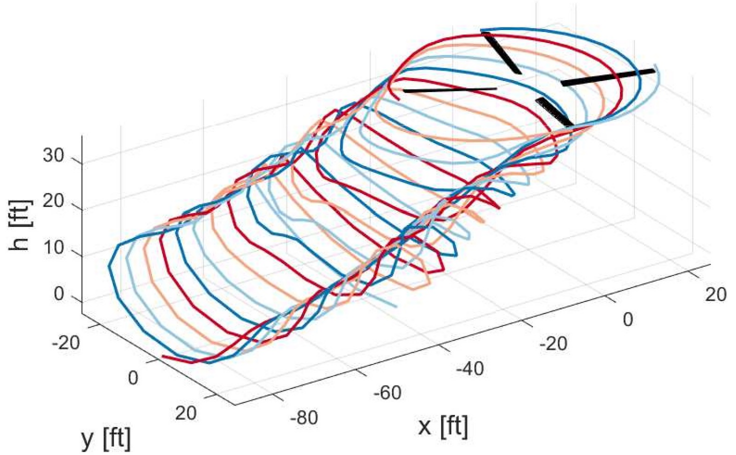
- State-variable implementation of aeromechanics
- Linearize dynamics with noise as output
- Active noise-abating flight control laws
- Cueing through full-body haptics (feel noise)

Funding

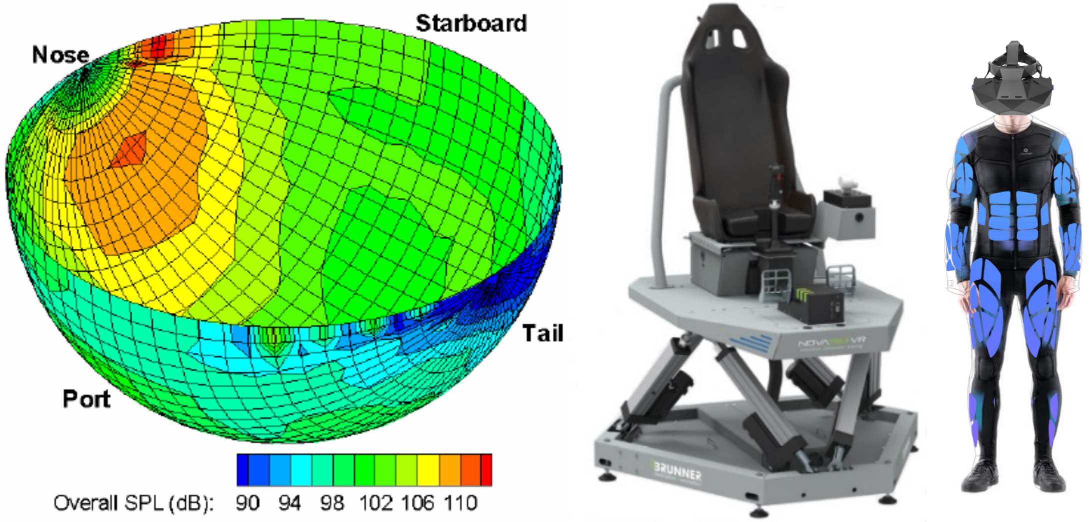
- UMD/Penn State **VLRCOE $461,000** – **Awarded**

Interactions

- Joe Horn, Ken Brentner (Penn State)



Time-periodic state-space free vortex wake model



Real-time prediction and cueing of rotorcraft noise via full-body haptics

Interactional Aerodynamics Modeling and Flight Control Design of Multi-Rotor Unmanned Aircraft Systems

Problem

- Rotor-on-rotor interactions predicted with very high-order models
- Simulations far slower than real-time
- Linearized models non tractable for control design

Solution

- Implementation of low-order dynamic inflow model for predicting rotor-on-rotor interactions
- Linearization and model-order reduction
- Flight control laws based on linear models that account for rotor-on-rotor interactions

Funding

- **U.S. Army $ 133,000** (Tom Berger) – **Awarded**

Interactions

- Roberto Celi (UMD)
- Mark Lopez, Emily Glover, Tom Berger, Ashwani Padthe (US Army CCDC)

Malloy TRV-80 Coaxial Quadcopter