Subscale Tiltrotor eVTOL Aircraft Dynamic Modeling and Flight Control Software Development

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NASA Langley Research Center

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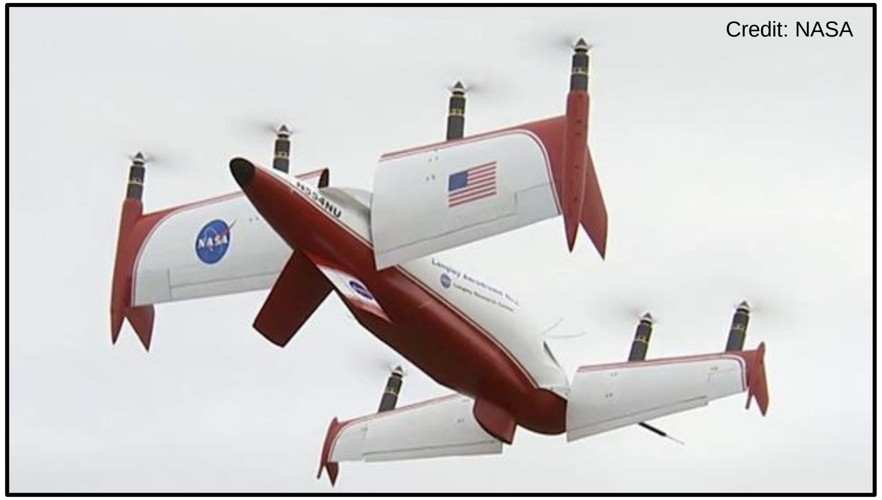
- Research motivation/challenges
- RAVEN-SWFT vehicle
- Static wind-tunnel testing
- Flight control system
- Programmed test inputs
- Free-motion wind-tunnel testing
- Flight-test approach/progress
- Concluding remarks
- Questions

Motivation

- Recent technology advancements enabling practical eVTOL aircraft
- Future Advanced Air Mobility (AAM) transportation system
- eVTOL vehicles are a new class of aircraft with numerous challenges
- New eVTOL aircraft modeling and control strategies are required
- Research aircraft needed for flight dynamics and controls research

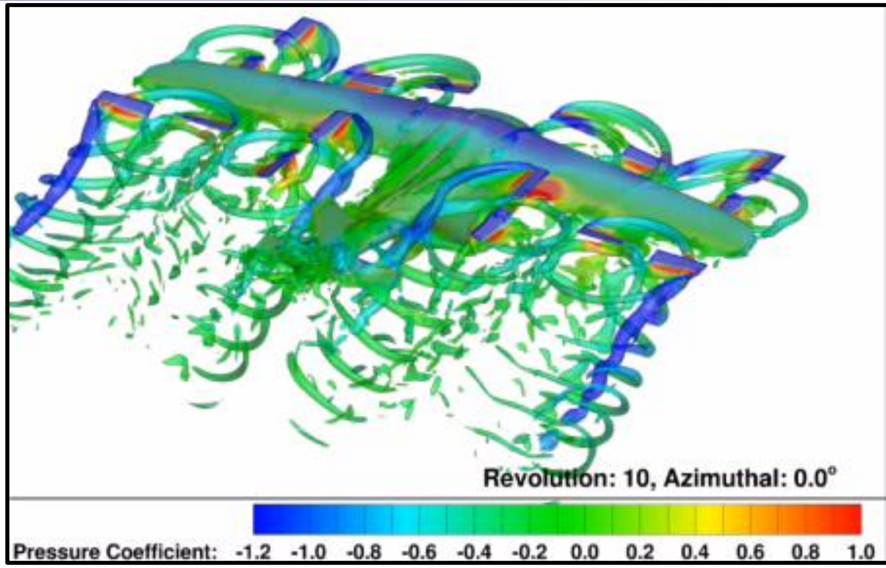
NASA GL-10 aircraft



NASA LA-8 aircraft

eVTOL Aircraft Modeling/Control Challenges

- Many control surfaces and propulsors
- Significant propulsion-airframe interactions
- Integrated *aero-propulsive* modeling
- High incidence angle *proprotor* aerodynamics
- Vehicle instability
- Large flight envelopes to characterize
- Rapidly changing transition aerodynamics
- Characteristics of multiple aircraft types
- Many different configurations



eVTOL aircraft CFD simulation.

Credit: Brian G. Allan (NASA Langley)

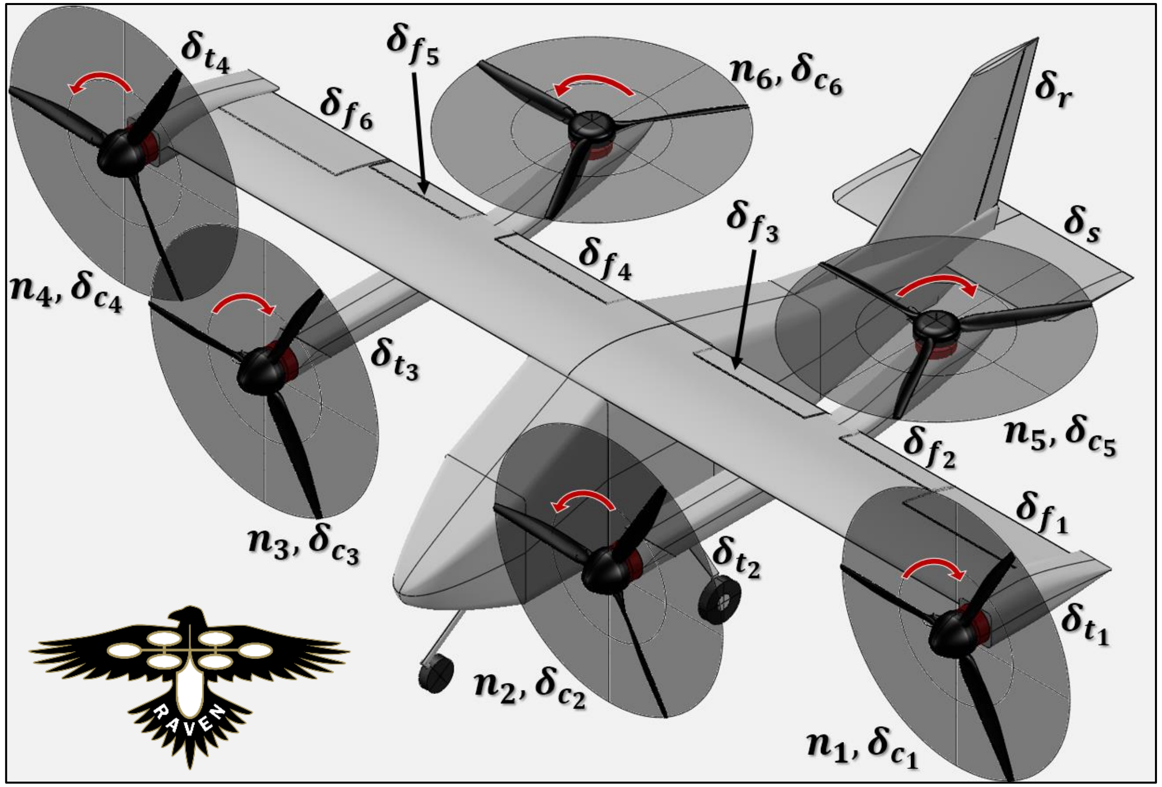
1,100+ known eVTOL aircraft concepts!
Reference: https://evtol.news/aircraft

eVTOL vehicle configurations exhibit highly complex, nonlinear aerodynamics

Advanced Air Mobility (AAM)

RAVEN eVTOL Vehicle

- RAVEN – **R**esearch **A**ircraft for e**V**TOL **E**nabling Tech**N**ologies[1]
- Tiltrotor eVTOL configuration with six variable-pitch proprotors
- Vehicles at different scales
- 24 independent control effectors
  - Six proprotor speeds $(n_1, n_2, \ldots, n_6)$
  - Six collective angles $(\delta_{c_1}, \delta_{c_2}, \ldots, \delta_{c_6})$
  - Four nacelle tilt angles $(\delta_{t_1}, \delta_{t_2}, \delta_{t_3}, \delta_{t_4})$
  - Six flaperons $(\delta_{f_1}, \delta_{f_2}, \ldots \delta_{f_6})$
  - Stabilator (δ_s) and rudder (δ_r)
- Built for modeling/controls research



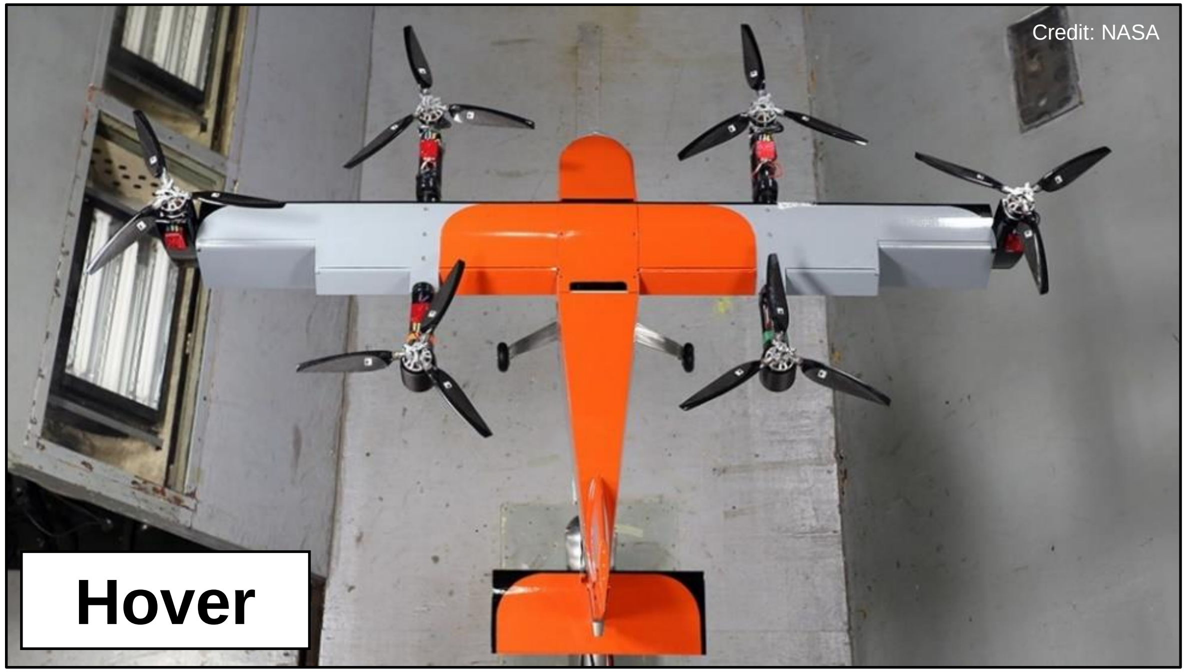
RAVEN control effector definitions.

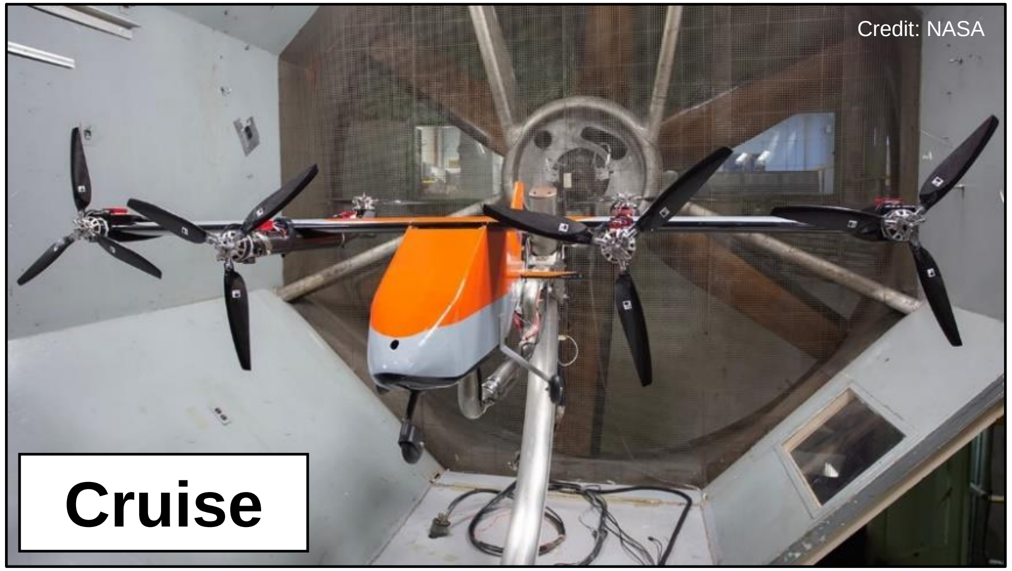
1. German, B. J., Jha, A., Whiteside, S. K. S., and Welstead, J. R., "Overview of the Research Aircraft for eVTOL Enabling techNologies (RAVEN) Activity," *AIAA AVIATION Forum*, June 2023.

RAVEN-SWFT

Research **A**ircraft for e**V**TOL **E**nabling Tech**N**ologies (RAVEN)
Subscale **W**ind-Tunnel and **F**light **T**est (SWFT) Vehicle[1]

- Wind-tunnel and flight-test research
- Similar scale to NASA LA-8 with expanded utility
- 28.6% scale version of 1000-lb class vehicle
- 37 lbs, 5.7 ft wingspan, 19.5 in diam. proprotors





1. Geuther, S. C., Simmons, B. M., and Ackerman, K. A., “Overview of the Subscale RAVEN Flight Controls and Modeling Testbed,” *VFS 80th Annual Forum*, May 2024.

RAVEN-SWFT Modeling and Controls

Flight Testing

↕ Comparison

Wind-Tunnel Testing

↕ Comparison

Computational Predictions

RAVEN-SWFT Flight Dynamics Model

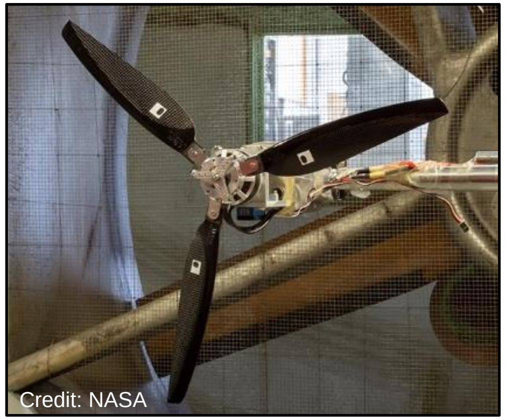
Flight Control System Development

Research Advancement and Toolchain Validation <u>Enabled by RAVEN-SWFT</u>

RAVEN-SWFT Wind-Tunnel Testing

Langley 12-Foot Low-Speed Tunnel

- Isolated proprotor testing[1]
- Static full-airframe testing[2]
- Dynamic free-motion testing[3]



Proprotor

Powered-airframe

RAVEN-SWFT wind tunnel tests.

Advanced Test Techniques

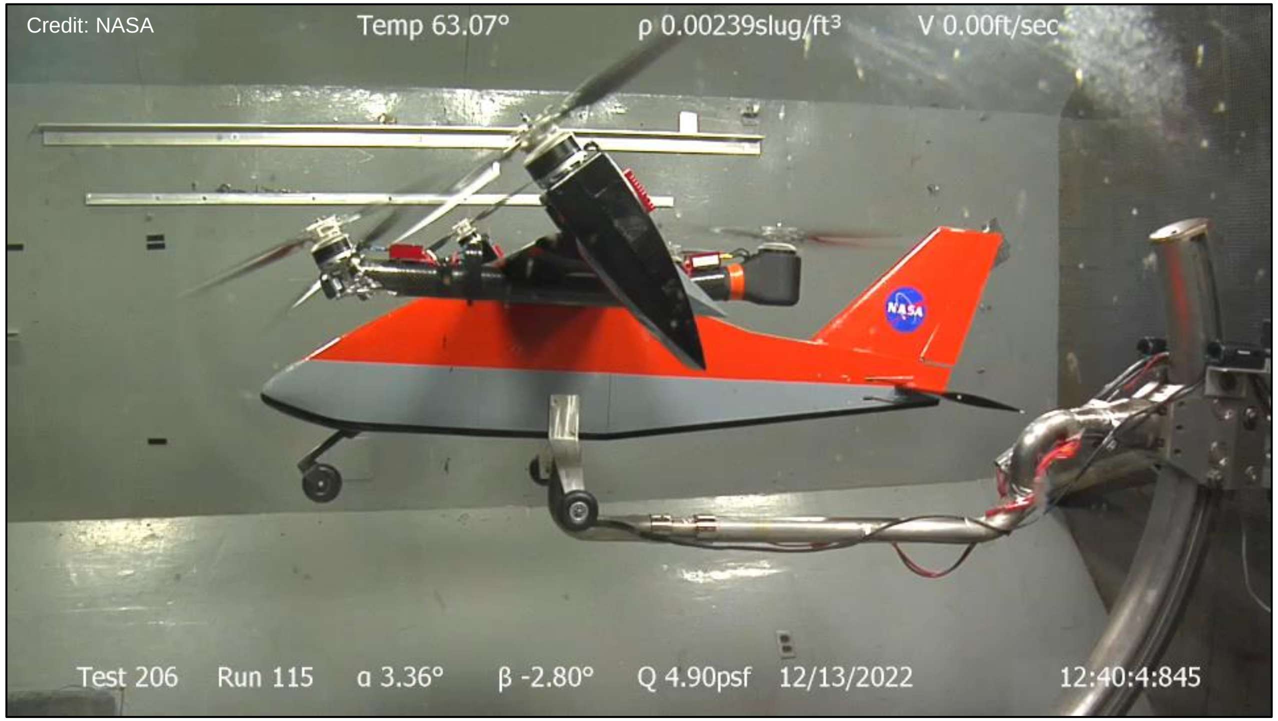
- Design of experiments (DOE)
- Response surface methods (RSM)
- Programmed test inputs (PTI)
- Three degree-of-freedom (3DOF)

Benefits

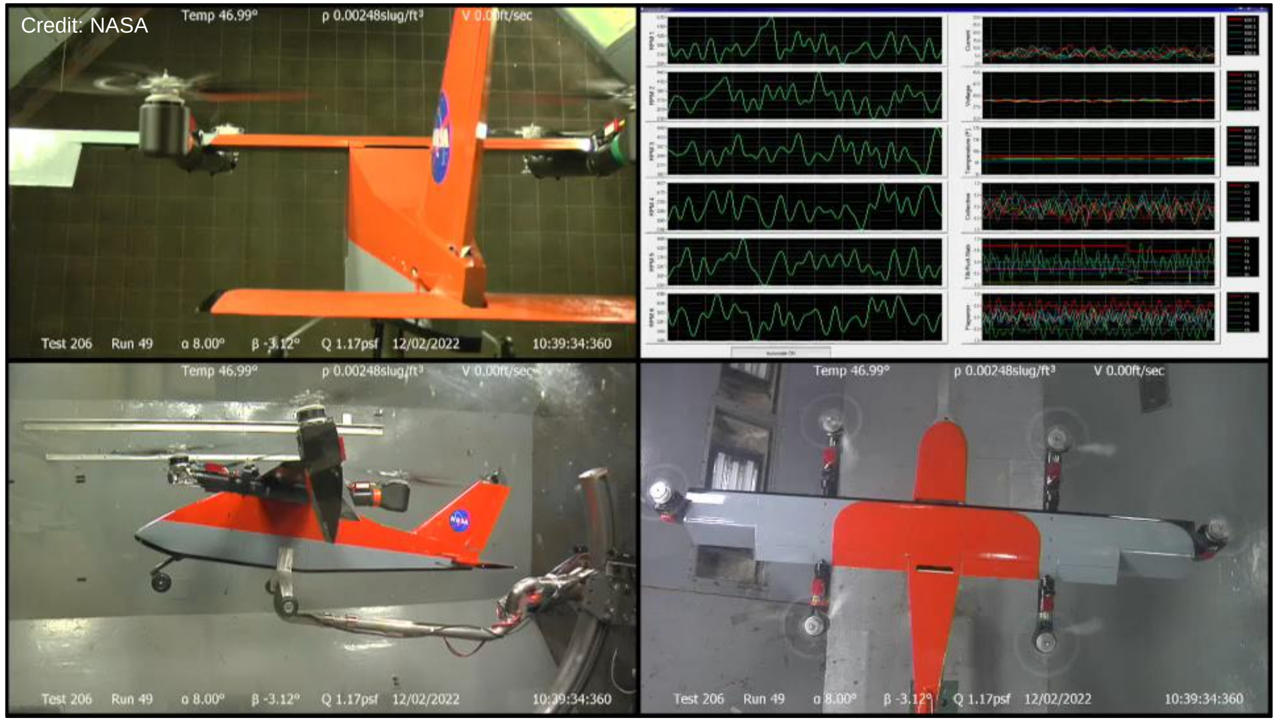
- Flight simulation development
- Flight control system design
- Validation of prediction tools
- Data/models that can be published

1. Simmons, B. M., “Efficient Variable-Pitch Propeller Aerodynamic Model Development for Vectored-Thrust eVTOL Aircraft,” *AIAA AVIATION 2022 Forum*, June 2022.
2. Simmons, B. M., and Busan, R. C., “Statistical Wind-Tunnel Experimentation Advancements for eVTOL Aircraft Aero-Propulsive Model Development,” *AIAA SciTech 2024 Forum*, January 2024.
3. Simmons, B. M., Ackerman, K. A., and Asper, G. D., “Aero-Propulsive Damping Characterization for eVTOL Aircraft Using Free Motion Wind-Tunnel Testing,” *AIAA SciTech 2025 Forum*, January 2025.

RAVEN-SWFT Powered-Airframe Testing



Static DOE/RSM testing (x20 speed).

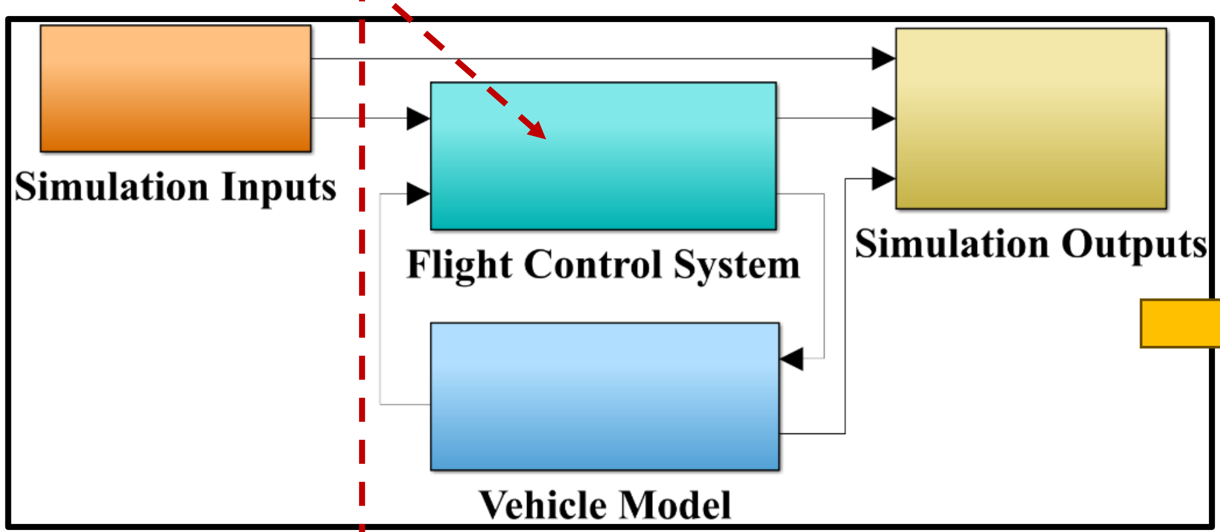


Hybrid PTI/DOE/RSM testing (x1 speed).

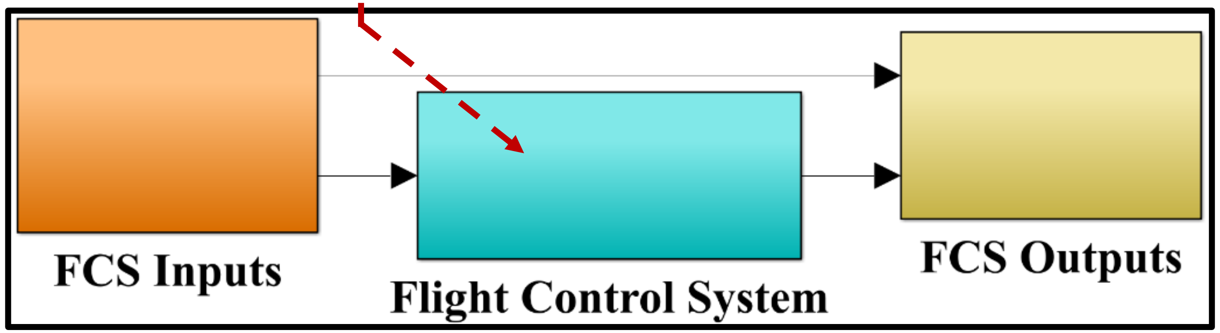
1. Simmons, B. M., "Evaluation of Response Surface Experiment Designs for Distributed Propulsion Aircraft Aero-Propulsive Modeling," *AIAA SciTech Forum*, January 2023.
2. Simmons, B. M., Morelli, E. A., Busan, R. C., Hatke, D. B., and O'Neal, A. W., "Aero-Propulsive Modeling for eVTOL Aircraft Using Wind Tunnel Testing with Multisine Inputs," *AIAA AVIATION Forum*, June 2022.
3. Simmons, B. M., and Busan, R. C., "Statistical Wind-Tunnel Experimentation Advancements for eVTOL Aircraft Aero-Propulsive Model Development," *AIAA SciTech 2024 Forum*, January 2024.

Simulation and Control System Development

Same Control Laws



Top-level of flight dynamics simulation.



Top-level of integrated flight control system.

RAVEN-SWFT piloted simulation in X-Plane.

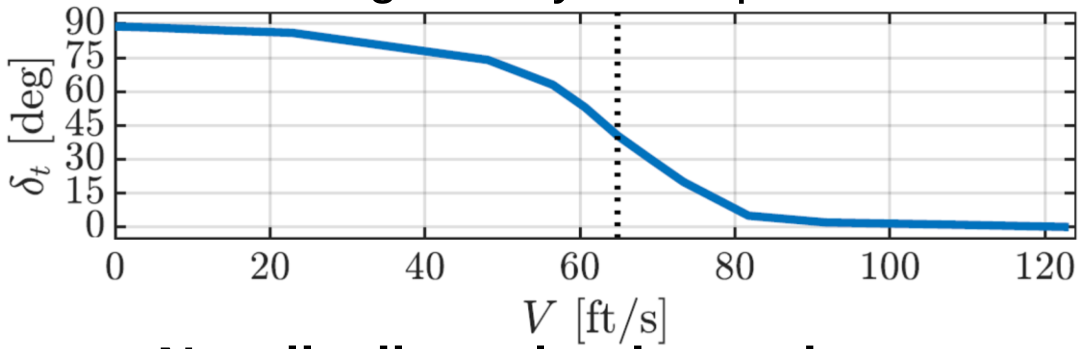
See the paper for additional details.

Unified Flight Control Algorithm Overview

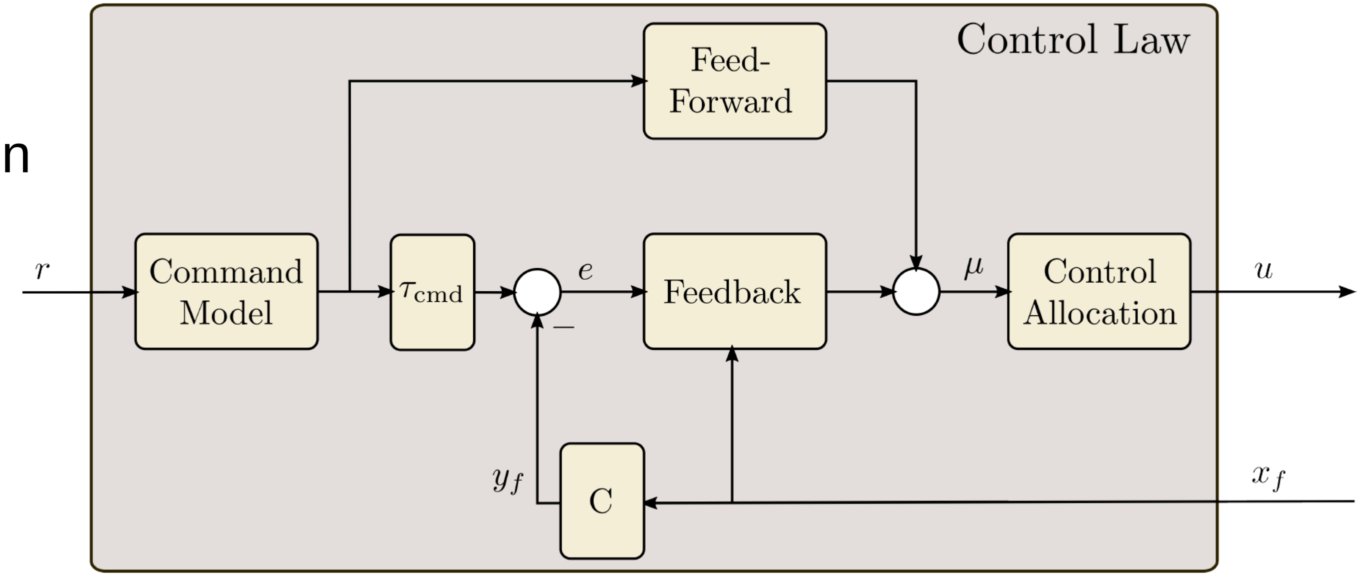
- Nested-loop architecture
  - Attitude-tracking inner loop
  - Velocity-tracking outer loop
- Model-based control design approach
  - Performance and robustness requirements
  - Linearization of simulation at trim conditions
  - Linear quadratic integral (LQI) model-following control framework with feedforward element
  - Weighted pseudo-inverse control allocation
  - Scheduling with dynamic pressure

Pilot command variables

Pilot Interface	Command Type	Unified Velocity (FCS Mode 2)
Right Stick ($\leftrightarrow$)	Lateral	Lateral Velocity ($\bar{v}$)
Right Stick ($\updownarrow$)	Longitudinal	Forward Velocity ($\Delta\bar{u}$)
Left Stick ($\leftrightarrow$)	Directional	Yaw Rate ($\dot{\psi}$)
Left Stick ($\updownarrow$)	Vertical	Vertical Velocity ($\bar{w}$)
Left Slider	Transition	Forward Velocity ($\bar{u}$)



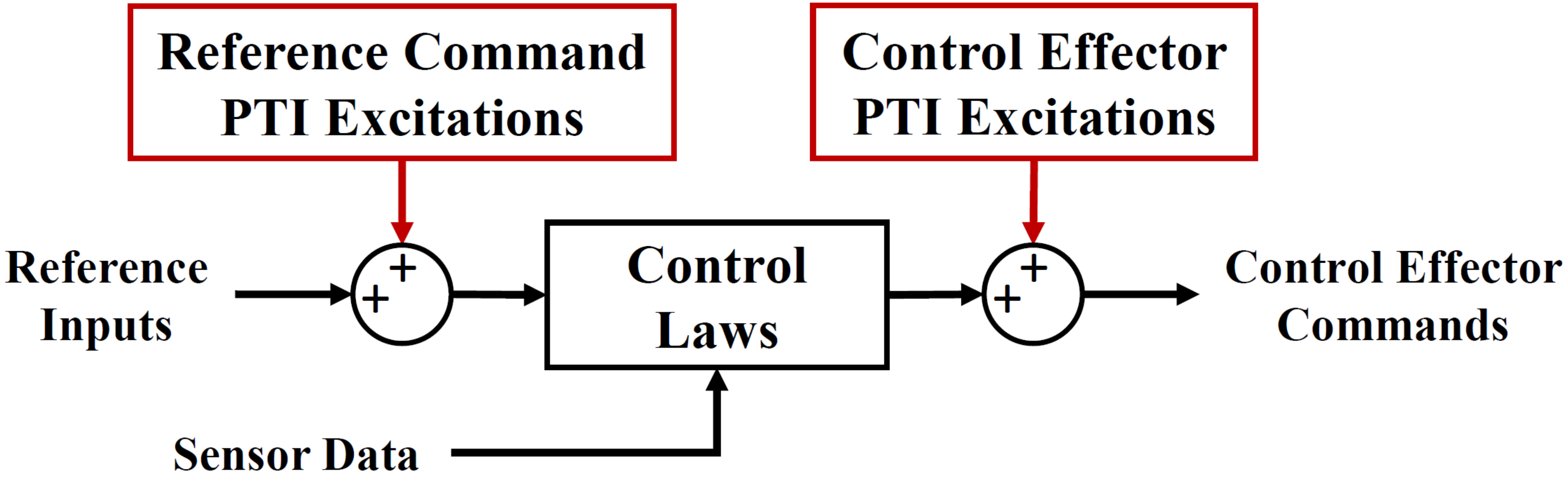
Nacelle tilt angle trim settings.



Inner-/outer-loop control law structure schematic.

Programmed Test Input (PTI) Injection

- **Objective:** generate informative data for model identification
- Multiple-input excitation required for efficient testing → multisines
- Other input types are also available (multistep, freq. sweep, etc.)
- Includes both reference command and control effector PTI excitations



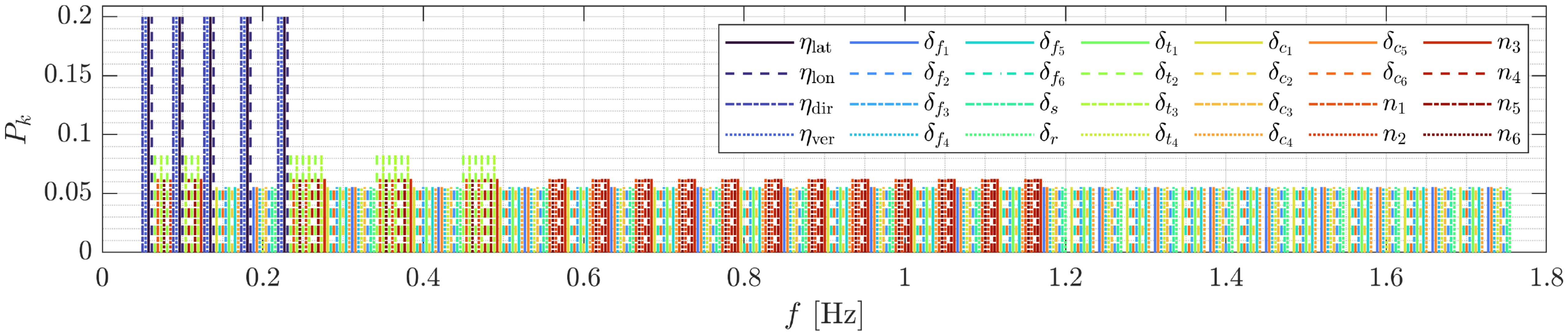
Programmed test input injections relative to the control laws.

Multisine Input Design

- Orthogonal phase-optimized multisine inputs[1,2]
- 28 unique multisine PTI excitation signals
- Simultaneous excitation in all axes
- Input design details are given in the paper

$$u_j(t) = \sum_{k \in K_j} A\sqrt{P_k}\sin\left(\frac{2\pi k t}{T} + \phi_k\right)$$

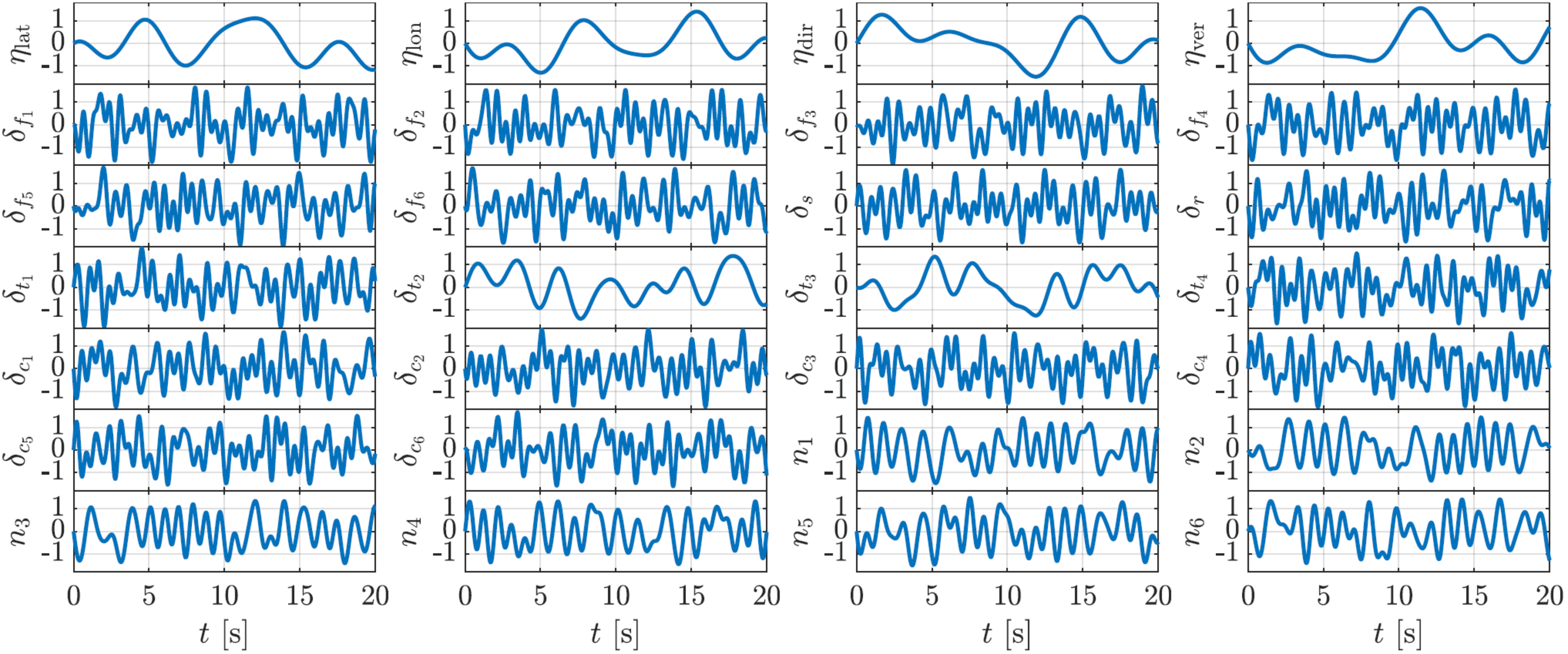
$u_j(t)$ – jth multisine signal
A – signal amplitude
P_k – kth power fraction
T – fundamental period
ϕ_k – kth phase angle



RAVEN-SWFT vehicle multisine input spectra.

1. Morelli, E. A., “Multiple Input Design for Real-Time Parameter Estimation in the Frequency Domain,” *13th IFAC Conference on System Identification*, Aug. 2003.
2. Morelli, E. A., and Klein, V., *Aircraft System Identification: Theory and Practice*, 2nd ed., Sunflyte Enterprises, Williamsburg, VA, 2016.

RAVEN-SWFT Multisine Signals



Normalized reference command and control effector multisine inputs.

Flight Control Software Integration

- **Goal:** streamlined process to deploy flight control algorithms developed in MATLAB/Simulink® onto the RAVEN-SWFT vehicle
- Refinement using low-cost, off-the-shelf, surrogate vehicles[1,2,3]
- MathWorks® UAV Toolbox and Support Package for PX4 Autopilots
- Pixhawk flight computer running custom PX4 firmware
  - PX4 outer- and inner-loop control laws are replaced with custom control laws
  - Other support functionality retained (estimation algorithm, safety logic, etc.)
- Control software updates built/deployed to the vehicle in <5 minutes

1. Asper, G. D., and Simmons, B. M., "Rapid Flight Control Law Deployment and Testing Framework for Subscale VTOL Aircraft," NASA TM–20220011570, September 2022.
2. Asper, G. D., Simmons, B. M., Axten, R. M., Ackerman, K. A., and Corrigan, P. E., "Inexpensive Multirotor Platform for Advanced Controls Testing (IMPACT): Development, Integration, and Experimentation," NASA TM–20240000223, March 2024.
3. Comer, A. M., Simmons, B. M., and Asper, G. D., "Design, Simulation, and Flight Testing of a Multi-Purpose VTOL Flight Control System," NASA TM–20250000954, To be published.

Additional Software Development Aspects

- Flight dynamics simulation subsystems
- Flight control system integration subsystems
- Control law design and tuning approach
- Trim strategy
- Flight control modes
- Takeoff and landing sequence
- RC transmitter and ground control station (GCS) commands
- Sensors and data acquisition
- Software assurance
- Airworthiness considerations

See the paper for additional details.

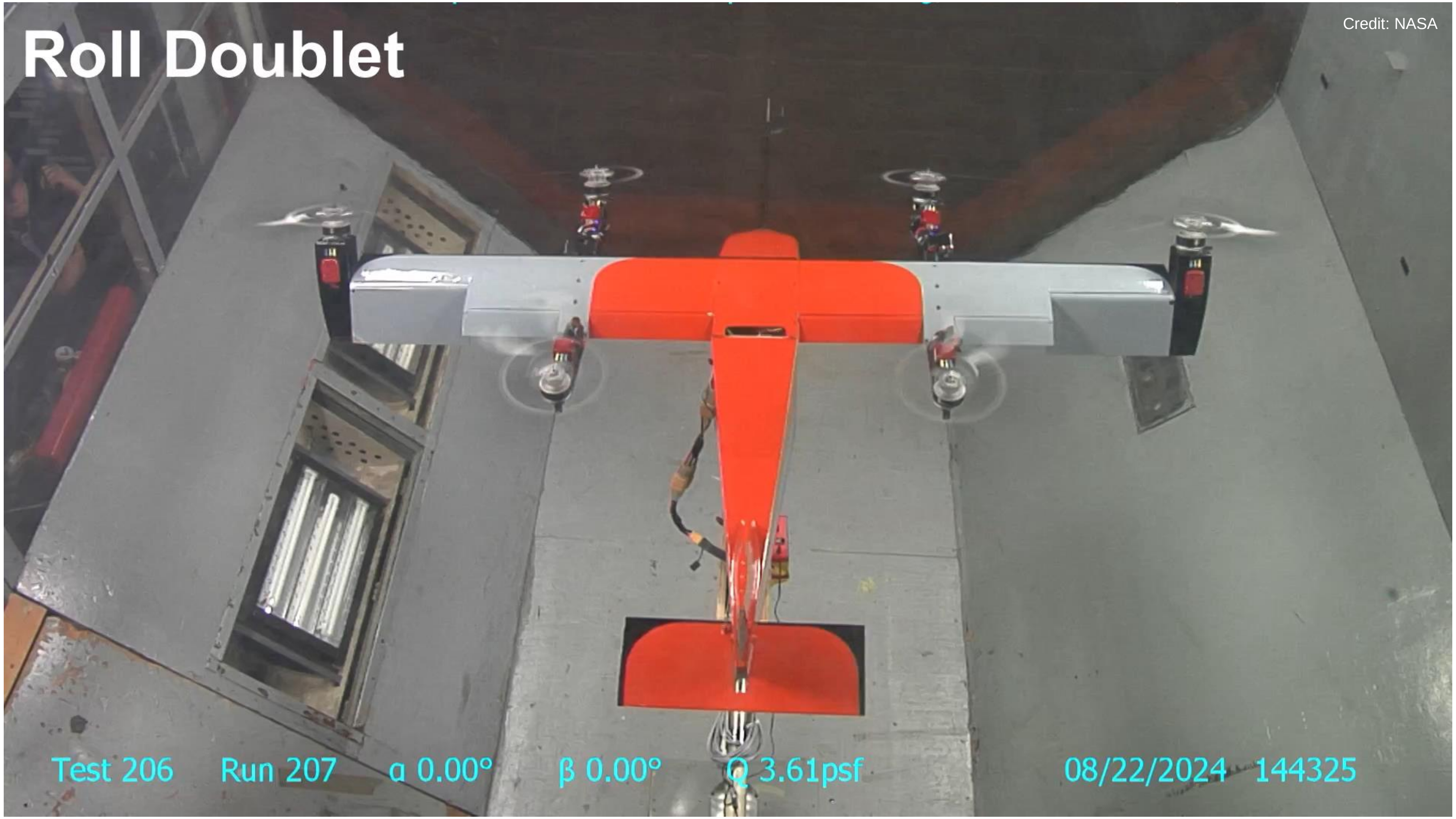
Three Degree-of-Freedom (3DOF) Testing

- New 3DOF rig designed and built in-house[1]
  - Free rotational motion
  - Aerodynamic damping characterization
  - Flight control algorithm evaluation
- Custom RAVEN-SWFT 3DOF control system
  - Model-based control design approach
  - Tracks commanded attitude angles
  - Scheduling with dynamic pressure
  - Programmed test input (PTI) injection capability
  - Control algorithm deployed to an onboard Pixhawk
- Wind-tunnel testing approach
  - Dynamic pressure set using the wind-tunnel system
  - RC transmitter and GCS computer command vehicle
  - Onboard instrumentation – no balance
  - Similar hardware and software used for flight testing

RAVEN-SWFT mounted on a 3DOF rig.

1. Credit: Ron Busan, Flight Dynamics Branch, NASA Langley

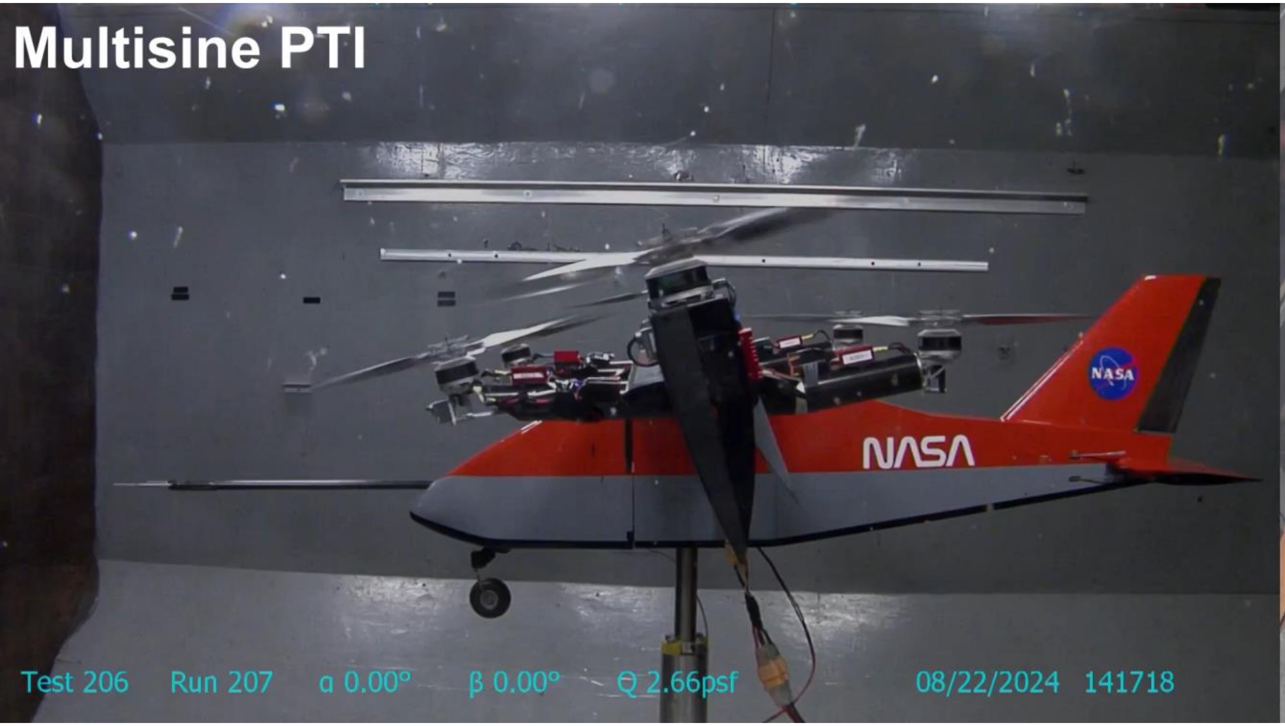
RAVEN-SWFT 3DOF Test Video

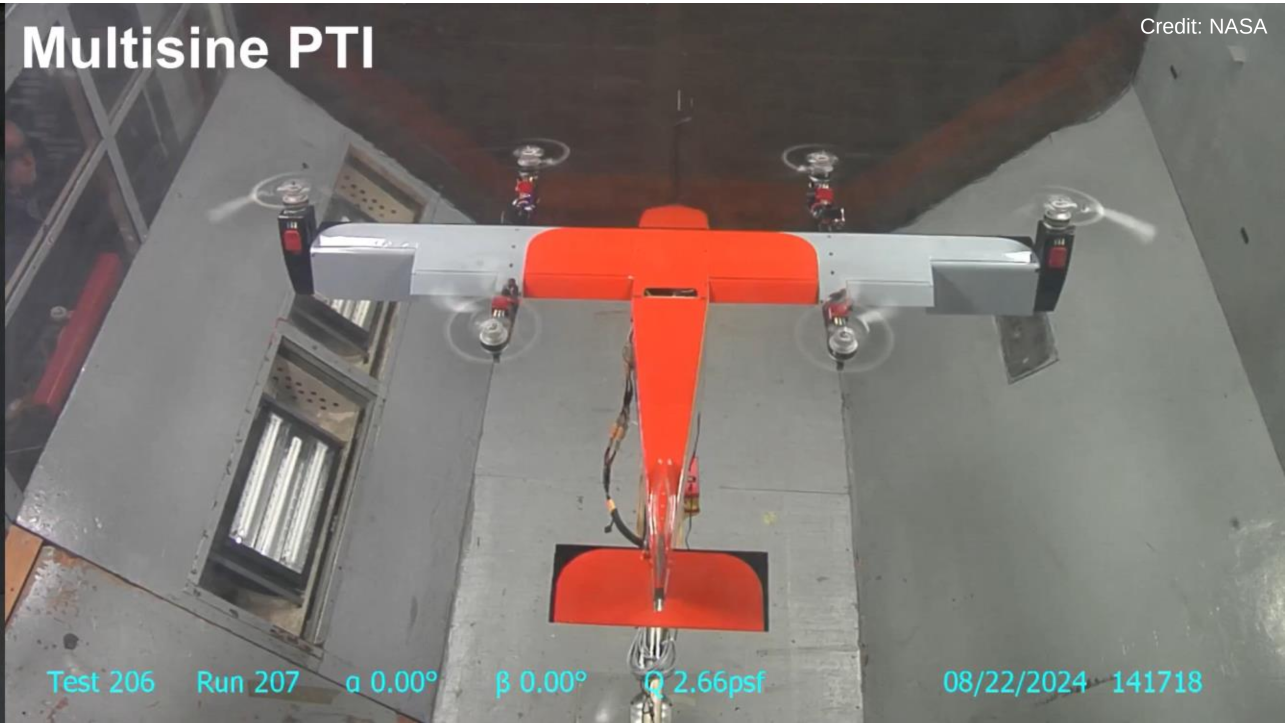


Attitude step commands at $\overline{q}$ = 3.79 lbf/ft^2.

RAVEN-SWFT 3DOF Multisine Maneuver

- PTIs are injected into the attitude and control effector commands
- All aircraft dynamics of interest are simultaneously excited
- Flight controller stabilizes the vehicle and tracks the commanded attitude





Multisine PTI excitations at $\bar{q}$ = 2.75 lbf/ft^2.

RAVEN-SWFT Tethered Flight Testing

- NASA CERTAIN Range, Vertiport #2
- Tether suspended above the vertipad using a large articulating boom lift
- Verification of hover flight controller

RAVEN-SWFT Tethered Flight Testing

RAVEN-SWFT Hover Free Flight Testing

- NASA CERTAIN Range, Vertiport #2
- Verification of hover flight controller
- 28 component multisine PTI enabled on first free flight

RAVEN-SWFT Hover Free Flight Testing

RAVEN-SWFT Hover Multisine Maneuver

Credit: NASA

Low-Speed Transition Flight Test

NASA Langley CERTAIN Range Runway/Vertiport #1

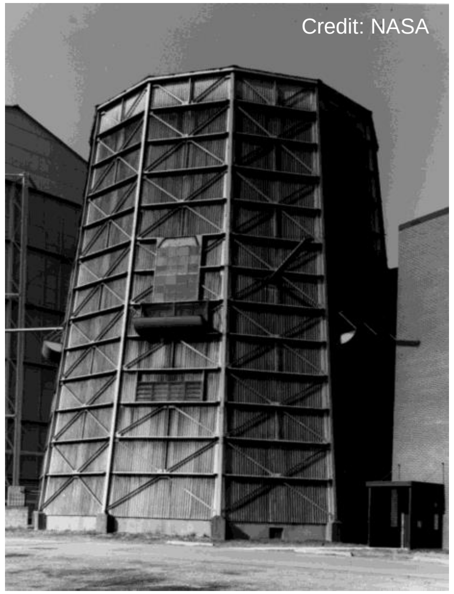
Credit: NASA

Concluding Remarks

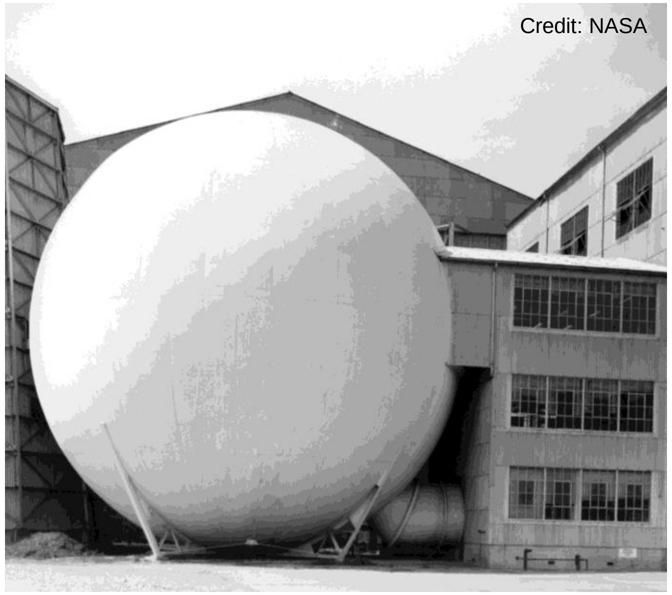
- eVTOL aircraft present new modeling and flight control challenges
- RAVEN-SWFT developed to advance modeling and controls research
- Paper provides details on modeling and flight control software development
- Enabling extensive wind-tunnel and ongoing flight testing
- Current focus on RAVEN-SWFT transition flight envelope expansion
- Techniques can be applied for many current and future vehicles

Coming Soon: NASA Langley FDRF

- Flight Dynamics Research Facility (FDRF)
- Combining/expanding capabilities of:
  - 20-Foot Vertical Spin Tunnel (VST)
  - 12-Foot Low-Speed Tunnel (LST)
- Scheduled to open in 2025
- Similar vehicles and research flexibility



20-Foot VST



12-Foot LST

FDRF construction progress (May 14, 2025)

Fremaux, C. M., Simmons, B. M., Owens, D. B., Vicroy, D. D., Storch, D. B., “Development and Capabilities of the NASA Flight Dynamics Research Facility,” *AIAA SciTech Forum*, Jan. 2025.

Questions/Discussion – Thank you for attending.

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Related RAVEN-SWFT References

1. Simmons, B. M., "Efficient Variable-Pitch Propeller Aerodynamic Model Development for Vectored-Thrust eVTOL Aircraft," *AIAA AVIATION Forum*, June 2022.
2. Simmons, B. M., Geuther, S. C., and Ahuja, V., "Validation of a Mid-Fidelity Approach for Aircraft Stability and Control Characterization," *AIAA AVIATION Forum*, June 2023.
3. Simmons, B. M., and Busan, R. C., "Statistical Wind-Tunnel Experimentation Advancements for eVTOL Aircraft Aero-Propulsive Model Development," *AIAA SciTech Forum*, January 2024.
4. Geuther, S. C., Simmons, B. M., and Ackerman, K. A., "Overview of the Subscale RAVEN Flight Controls and Modeling Testbed," *Vertical Flight Society's 80th Annual Forum & Technology Display*, May 2024.
5. Simmons, B. M., Ackerman, K. A., and Asper, G. D., "Aero-Propulsive Damping Characterization for eVTOL Aircraft Using Free Motion Wind-Tunnel Testing," *AIAA SciTech 2025 Forum*, January 2025.