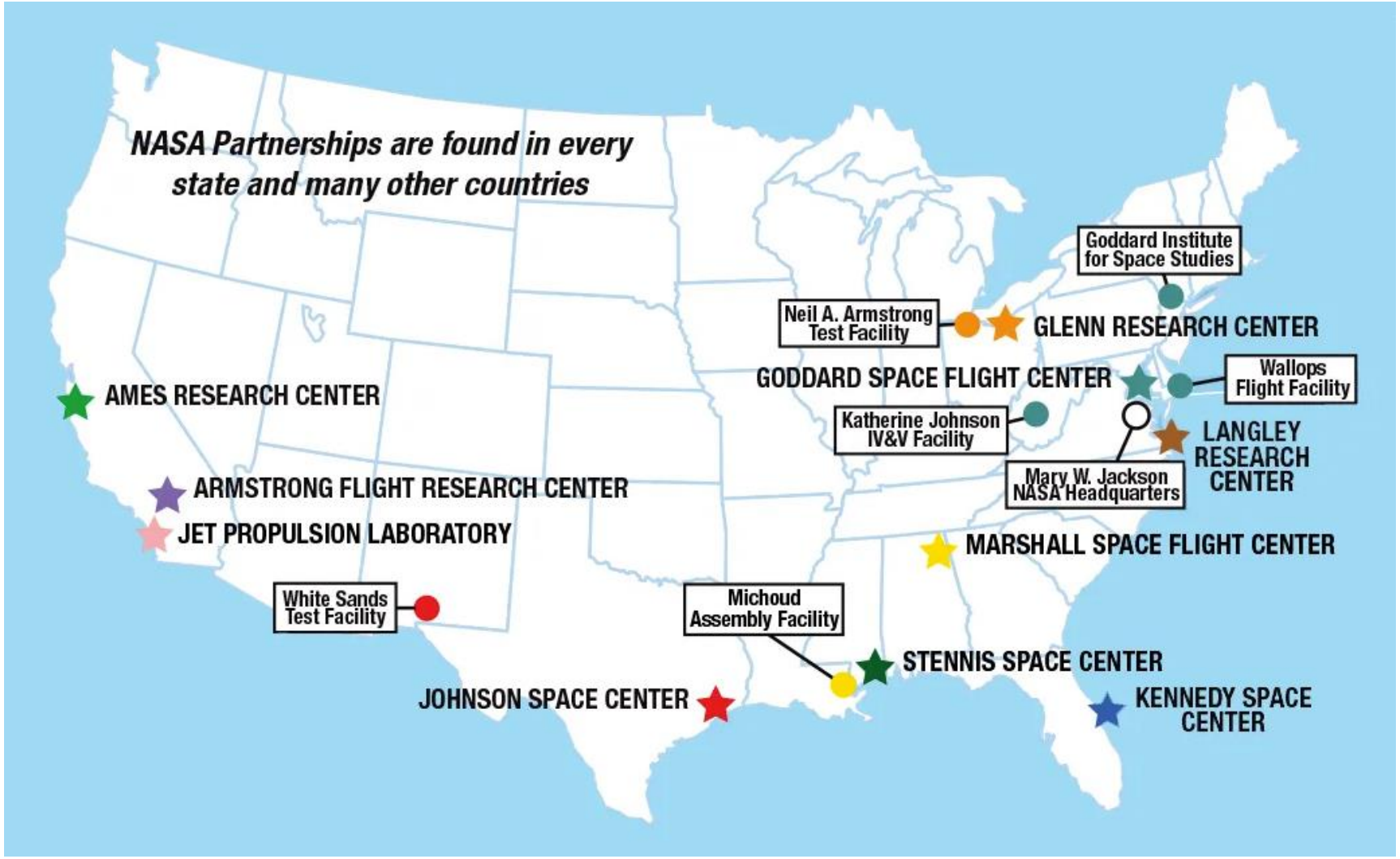
Flight Dynamics and Control Research at NASA Langley Research Center

Aerospace Control and Guidance Systems Committee
Meeting #134
Houston, TX
12—14 March 2025

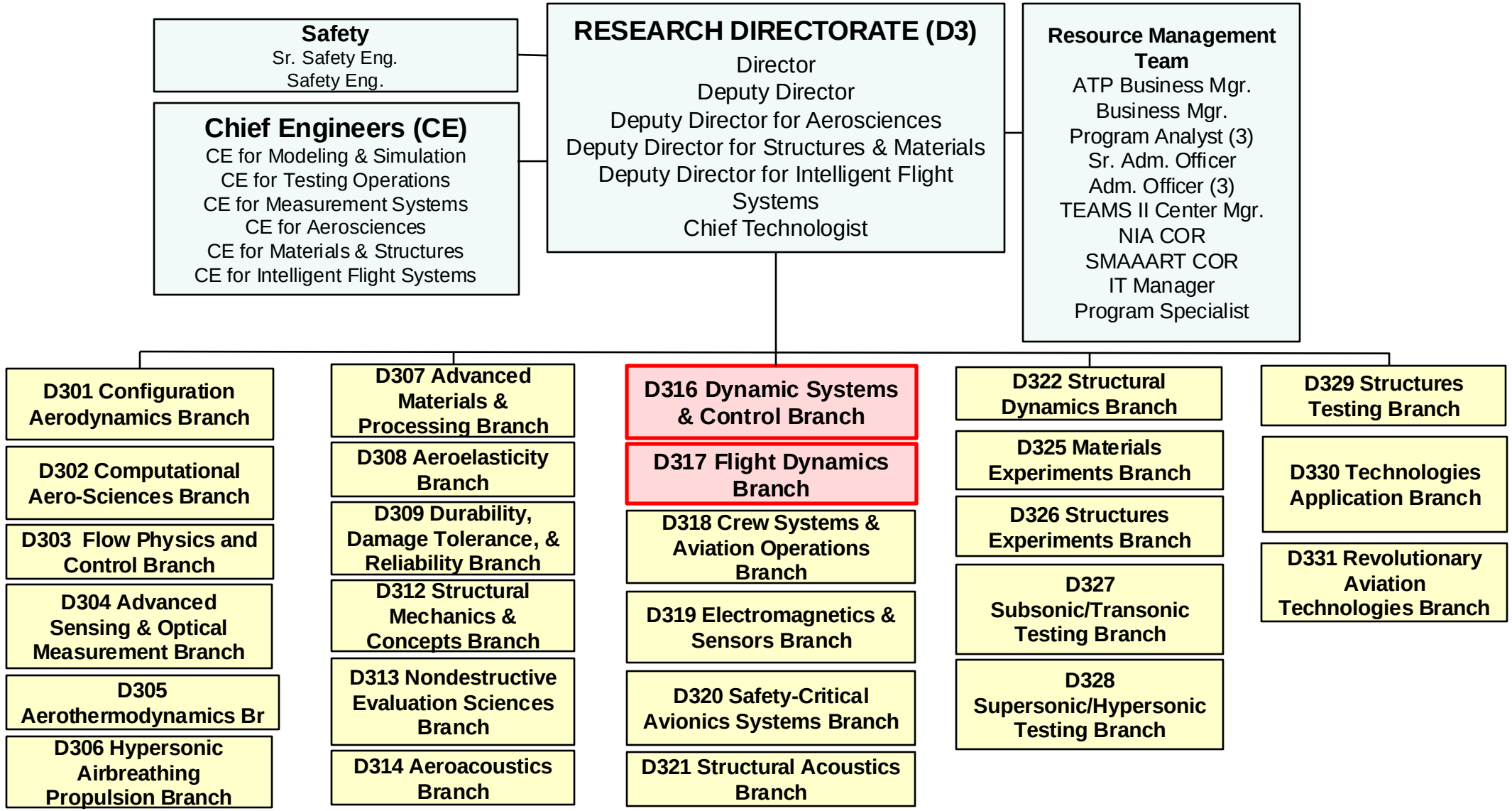




NASA Locations, Capabilities, and Points of Contact



Directorate Hierarchical Structure



X-59 Low Boom Flight Demonstrator

- Lockheed Martin (LM) is responsible for flight control design, development, and airworthiness.
- NASA Flight Dynamics Team provides independent oversight, analysis, and recommendations (when appropriate).
- Providing flight control and flying qualities assessments to LM upon release of new control laws.
- Closed-loop stability analysis.
- Handling qualities predictions (analytical & piloted simulation).
- Off-nominal considerations (sensor error/failures, control law modes, control surface failures, system failures, model uncertainty, S&C assessment outside operational environment).
- Piloted simulations that has provided handling qualities assessments, standard operating producers, and emergency procedures.
- Conducting assessments for flight readiness review.



Photo credit: Lockheed Martin Skunk Works

POC: Matthew Boucher, matthew.j.boucher@nasa.gov

X-66A Sustainable Flight Demonstrator



- Boeing is leading the effort for SFD with support from NASA.
- An MD-90 is being converted to the X-66A aircraft.
- Key modifications: replacement of wings, resizing of the fuselage.
- NASA LaRC controls & dynamics work will be:
  - Conducting wind tunnel test
  - Assisting with control law development
  - Assisting with airworthiness

The purpose of the Sustainable Flight Demonstrator (SFD) project is to engage with industry, academia, and other government organizations to identify, select, and mature key airframe technologies – such as new wing designs – that have a high probability of transition to the next generation single-aisle seat class airliner.

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Integrated Adaptive Wing Technology Maturation (IAWTM)

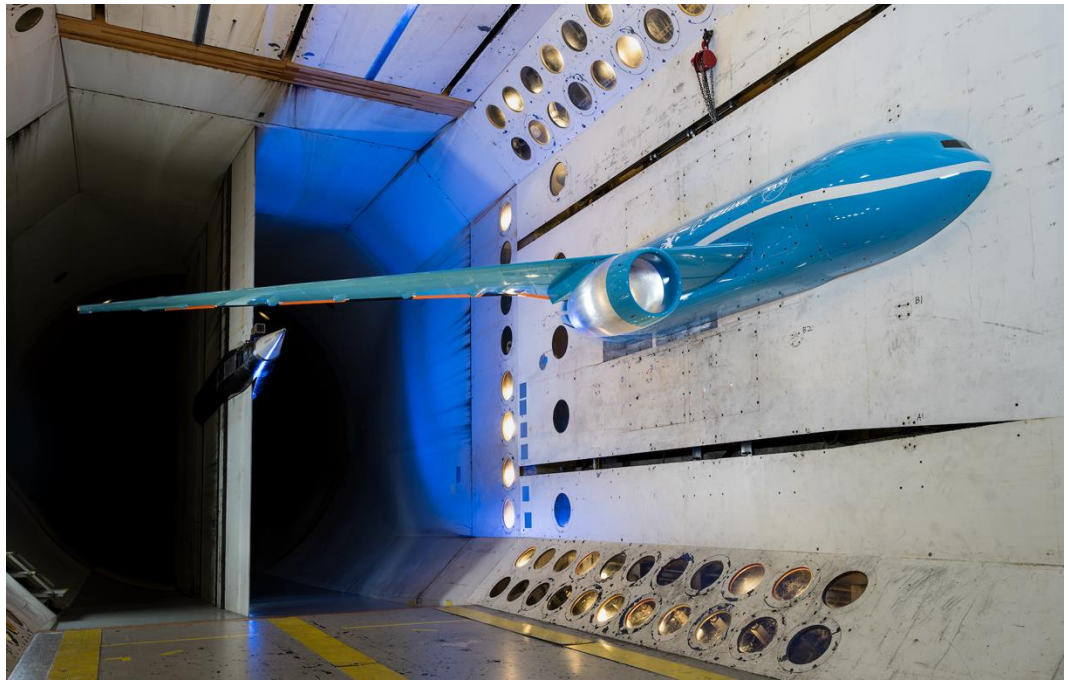
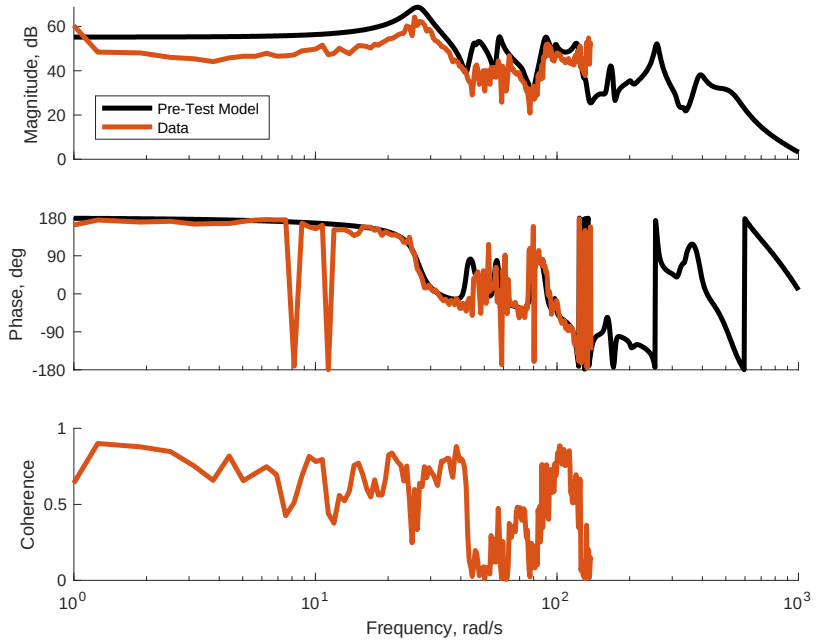


Photo credit: NASA / Mark Knopp

- Develop technologies to improve energy efficiency and lessen environmental impacts of transport aircraft.
- Validate control methodologies for real-time drag minimization, maneuver load alleviation (MLA), gust load alleviation (GLA), and active flutter suppression (AFS) architectures.
- Entry 1 (Jul.—Aug. 2024) for open loop.
- Entry 2 (expected Jun.—Jul. 2025) for closed-loop.

- System identification of aeroelastic models and component subsystem models.
- Efficient methods for static testing.
- Uncertainty quantification in FEM update.
- Active flutter suppression control law design:
  - Identically-located accelerometer and force (ILAF)
  - Modal control
  - Robust Control (H-infinity) with University of Minnesota



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Generalized Urban Air Mobility (GUAM) Simulation

What is it?

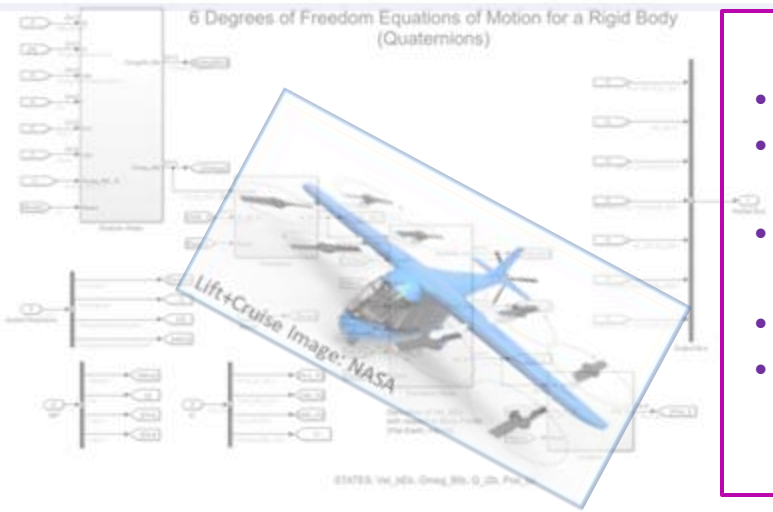
- Open source, **6-DOF, non-linear**, rigid body simulation framework for Urban Air Mobility (UAM) vehicles
- **Modular simulation** architecture facilities easy implementation of vehicle model, controller, sensor (perception), autonomy algorithms

What is in the initial release?

- Single NASA Lift+Cruise vehicle configuration
- **Two aero-propulsive models**: strip theory and polynomial models
- Baseline unified (across hover/ transition/cruise) **iLQR controller**
- **Aero/propulsor** effector and **failure models**
- Matlab-**autocode capable**
- **Compact, continuous trajectories** using piece-wise Berstein polynomials

Why is NASA releasing it?

- Foster **collaboration** to address wide array of research challenges for UAM autonomy
- Provide **common simulation** architecture for collaboration and performance comparison
- **Address barriers** of proprietary information, limited research staffs, and limited access to medium/high fidelity UAM models



What is in the next release?

- **High fidelity visualization**: Unreal Engine v4 & v5
- Ease of **sensor implementation** (e.g., camera lidar): Microsoft Airsim and CodexLabsLLC Colosseum
- **ROS2** HUMBLE **integration**: no Matlab toolbox required
- **Cognitive** (decision making) **architecture**/framework
- **Example Collision Avoidance**: Optimal Reciprocal Collision Avoidance (ORCA) integrated with Bernstein Polynomials

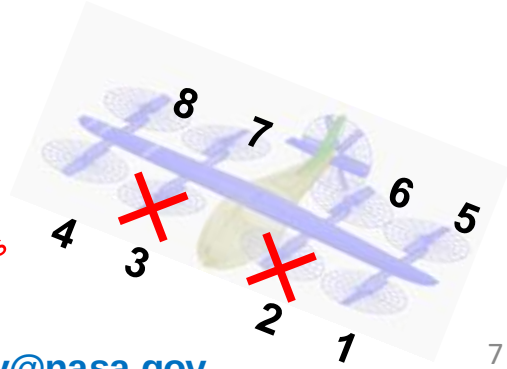
Challenge Problems:

- Provide **code & data** that formulates large **research challenges** for the **autonomous** UAM community
- **Examples**: collision avoidance, effector failure (control and flight envelope estimation), traffic pattern entry, trajectory replanning, etc.

GUAM Community:

GIT repo:
https://www.github.com/nasa/generic-urban-air-mobility-GUAM
Challenge Problems:
https://nari.arc.nasa.gov/ttt-ram/community

Perception
Aero-propulsive Modeling
Transition
Vehicle control
Cooperative & uncooperative collision avoidance
Flight envelope estimation
Control allocation
Dynamically feasible trajectory
Trajectory optimization
Cognitive architecture
Human machine interface
Safety guarantees



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Traffic Pattern Integration for Autonomous Vehicles

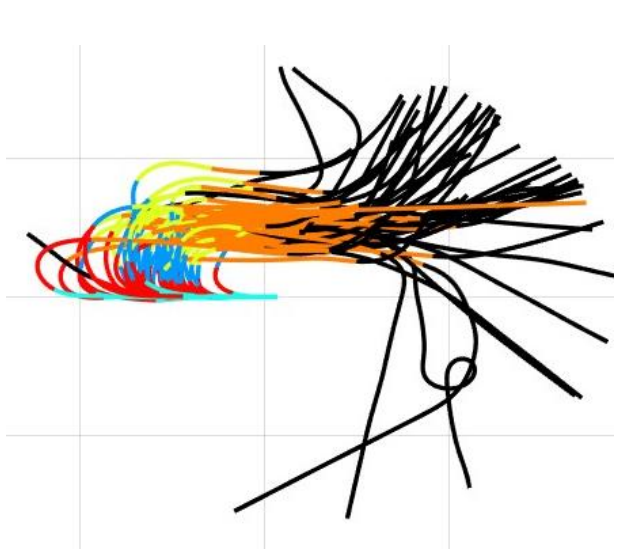
Developing a suite of algorithms to test and demonstrate autonomous integration into un-towered airspace, with or without intervehicle communication.

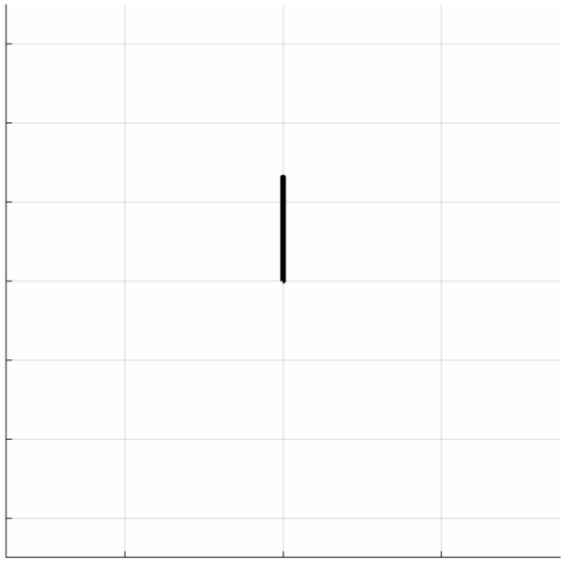
Flight Segmentation
Parameterize real trajectories for data-based algorithms and simulations.

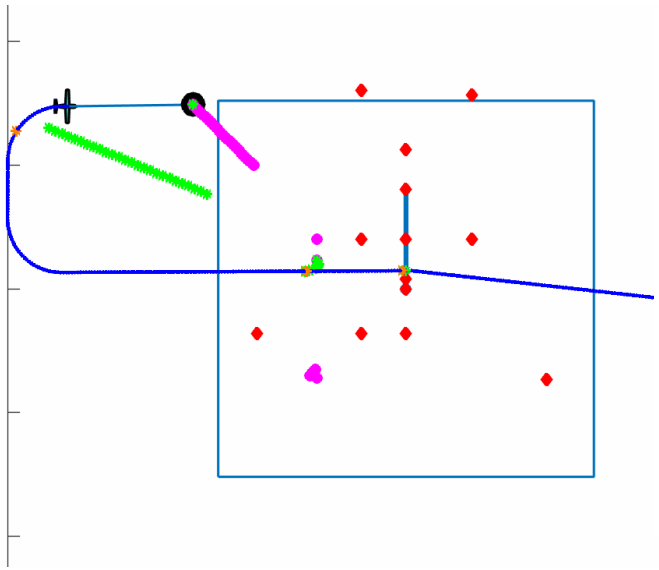
Air Traffic Generation
Custom or data-informed air traffic trajectories for benchmarking autonomy algorithms.

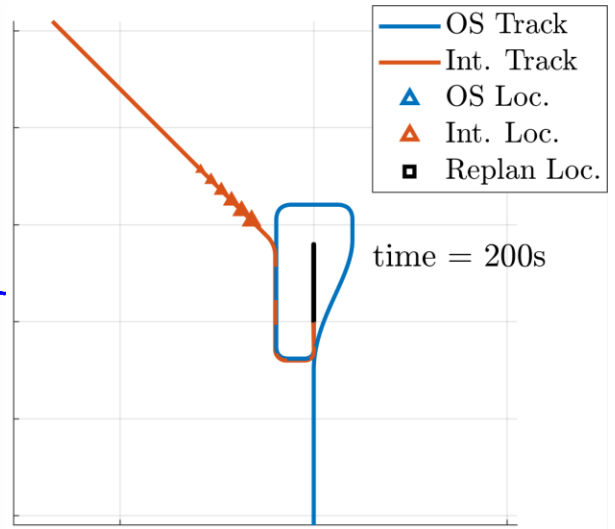
Air Traffic Prediction
Dynamically predict all reasonable approaches from current aircraft location to the runway.

Replanning
Update speed and entry type to avoid predicted collisions.









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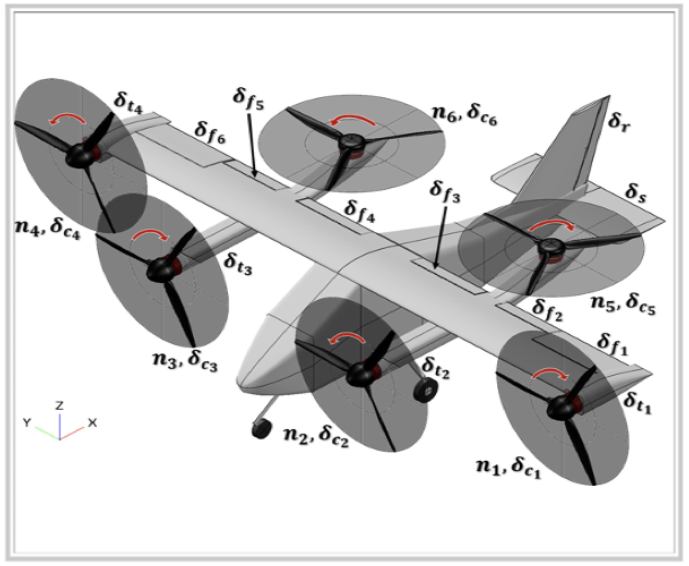
RAVEN – Research Aircraft for eVTOL Enabling TechNologies

- Built for modeling and flight control research.
- Tilt-rotor eVTOL aircraft with 6 variable-pitch propellers.
- Outboard and front inboard motors tilt, rear inboard motors fixed.
- 24 control effectors (6 propeller speeds, 6 propeller collective angles, 4 propeller tilt angles, 6 flaperons, stabilator, rudder).
- Vehicles at different scales.
- 1000-lb “full-scale” vehicle (NASA / Georgia Tech).
- Subscale wind-tunnel/flight test (SWFT) aircraft (NASA).
- 3 dynamic flight modes (hover, transition, cruise).
- Significant aero-propulsive interaction.





Controls research in the following areas:

- Custom full-envelope flight control laws
- Bare-airframe 3DOF wind tunnel flight control laws
- Powered 3DOF wind tunnel flight control laws
- Simulation development
- Wind tunnel and flight test support

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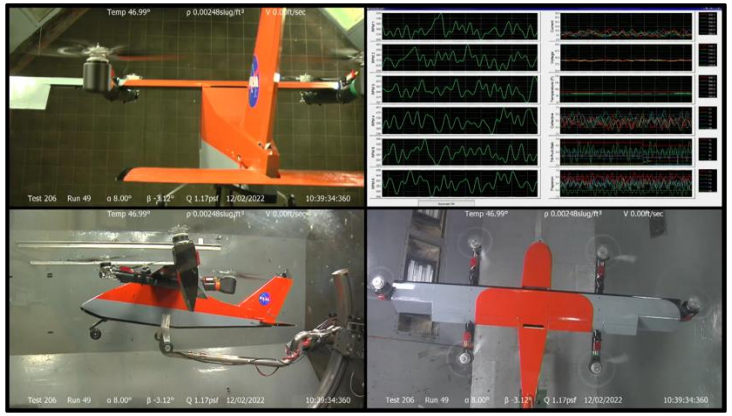
and Benjamin Simmons, Benjamin.m.simmons@nasa.gov

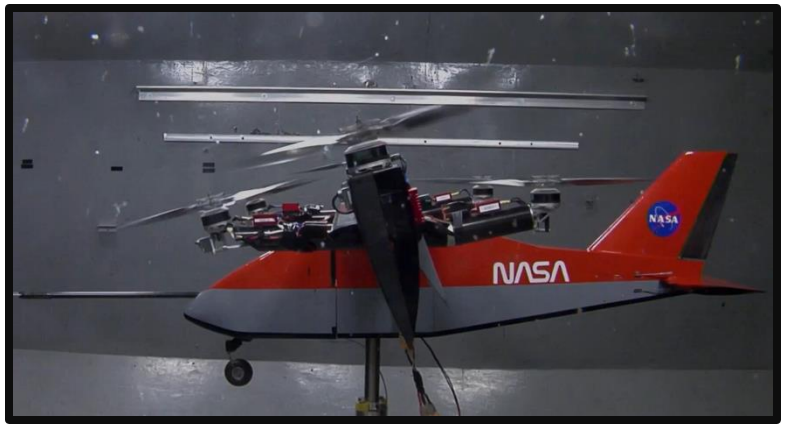
Aero-Propulsive Modeling for eVTOL Aircraft

Experiment Design
- Design of experiments (DOE)
- Response surface methods (RSM)
- Programmed test inputs (PTI)
- Full-envelope static/dynamic testing

Test Facilities
- NASA Langley 12-Foot Low-Speed Tunnel
- Various-fidelity computational methods
- NASA Langley CERTAIN flight-test range
- Future: Flight Dynamics Research Facility



Static PTI + DOE/RSM testing (x1 speed)



3DOF testing with PTIs (x1 speed)



Hover flight testing with doublets (x1 speed)

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Space Launch System and Orion

- Development of an independent simulation of SLS ascent trajectory
- Non-linear 6-DOF simulation based on STARS (internal MATLAB-based simulation)
- Block 1 and Block 1B vehicles
- Verification of simulation tools for SLS
- Time and frequency domain verifications with other linear and non-linear simulation tools
- Design, evaluation, and flight test data analysis of ascent system identification inputs (Programmed Test Inputs)
- Frequency domain verification of simulations





- Orion Launch Abort System (LAS) GNC Design & Con-ops Trade Studies and Performance Assessments
- Support Orion G&C Program Reviews, Verification Analysis, and Generation of Trajectory Data Products
- Pad Abort-1 and Ascent Abort-2 Flight Test G&C Analysis and Risk Reduction
- Artemis-2 LAS Abort and Entry, Descent, and Landing G&C Analysis and Risk Reduction
- Artemis-2 LAS Jettison Separation Clearance Analysis
- Dynamic Stability Assessment of Orion Crew Module During EDL (Artemis I and Artemis II)

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Human Landing System

Convex Optimization-based Guidance during powered descent

- Working with commercial partners (SpaceX, Blue Origin) and other NASA centers (MSFC, JSC) on applying state-of-the-art methods such as Sequential Convex Programming and Model Predictive Control that generate trajectories that satisfy mission, state, and control constraints both offline and real-time

Low-g slosh modeling

- Collaboration with NESC on the development of a mechanical low-g slosh model that can be readily integrated into GNC simulations
- Crucial for current and future space vehicles with large amount of propellant onboard





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Rendezvous Proximity Operations and Docking

- Insight activities on major RPOD activities including Starship-Gateway, Starship-Depot during propellant transfers

Crew Training and Manual Piloting during descent and free-flight

- Collaboration with LaRC D107 and D318 on exploration of different manual control algorithms
- Part of HLS Crew training portfolio
- In-flight trainer (similar idea as the Lunar Landing Training Vehicle) studies

Landing Dynamics

- Insight activities with LaRC D206 on vehicle landing stability and tip-over control design

Special Issue in the Journal of Aircraft



JOURNAL OF AIRCRAFT
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Check for updates

Introduction to the Advances in Aircraft System Identification from Flight Test Data Virtual Collection

https://doi.org/10.2514/1.C037583

Advances in Aircraft System Identification from Flight Test Data Virtual Collection:
https://arc.aiaa.org/toc/ja/Virtual+Collection/1

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AIRCRAFT system identification is the process of determining mathematical models for aircraft from flight test data. As aircraft designs have become more complex and the capabilities of computers and experimental hardware have improved, system identification has become increasingly important for the efficient development of new aircraft. Applications for aircraft system identification include comparisons to theoretical predictions, simulation development and updating, stability and control assessment, control law development, flying qualities assessments, and stability margin extraction, among others.

During 2004–2005, Dr. Ravindra Jategaonkar from the Deutsches Zentrum für Luft- und Raumfahrt (DLR) organized an excellent two-part special section in the *Journal of Aircraft* on aircraft system identification. The primary motivations for that special section included reflecting on the recent expansion of techniques and applications of aircraft system identification, and addressing the perception that the practical utility of aircraft system identification was not well known. A total of 18 papers were published from different institutions, countries, and sectors of the aerospace community.

In the almost 20 years that have elapsed since that special section, aircraft system identification has continued to advance and expand in importance, as evidenced by its widespread presence. For example, the AIAA Atmospheric Flight Mechanics (AFM) conference typically hosts several sessions related to aircraft system identification at the yearly SciTech Forum. Likewise, papers on the subject routinely appear in the *Journal of Aircraft* and the *Journal of Guidance, Control, and Dynamics*. Short courses are periodically given by subject experts, and the number of graduate courses offered by universities has grown. Several software packages, which use a variety of methods, can now be accessed to perform system identification analyses. Perhaps most noteworthy is that in the year following the 2004–2005 special section, three textbooks on aircraft system identification from flight test data [1–3] were published. All three of these books are currently in their second editions [4–6] and have expanded content.

In talking with colleagues, it was apparent that the methods and applications have advanced significantly, and that another special section, now called a Virtual Collection (VC), in the *Journal of Aircraft* was warranted for sharing the current state of the art in aircraft system identification. A total of 58 people spanning 34 institutions from 8 countries (USA, Canada, Brazil, United Kingdom, France, Germany, the Netherlands, and Australia) and 3 sectors (government, industry, and academia) were invited to contribute a paper summarizing experiences and methods used at their institution related to aircraft system identification. For many reasons, including lack of time and the sometimes restrictive nature of information related to aerospace vehicles, about two-thirds of the organizations did not participate. Therefore, several groups of experts are absent from this VC. In the end, 10 organizations participated. The quality of the papers from the participating authors is high, and the contributions represent a balanced view of current and active practitioners.

The goal of this VC was to summarize experiences with aircraft system identification at leading institutions and to present methods that have been proven for specific problems, in particular those developed over the last 20 years. The primary focus was on system identification from flight test data rather than from simulation data or wind tunnel tests, although those subjects are also important.

The papers assembled for this VC exhibited several common themes, despite the fact that the papers describe work at different organizations. The vehicles studied were mostly small and low-cost aircraft or manned fixed-wing and rotary-wing aircraft, but there were also hypersonic vehicles and launch/re-entry vehicles. The dynamics of interest extended beyond the traditional rigid-body fixed-wing dynamics at low angles of attack and included more comprehensive models with aeroelasticity, high-order aerodynamics and rotor dynamics, icing, turbulence, high angles of attack and sideslip angles, and global nonlinear aerodynamics. In addition, the methods used to perform the system identification analysis are being advanced in similar areas of interest. Techniques are presented for creating or updating global model databases, designing efficient experiments, exploring time-varying dynamics, identifying models in the presence of high-gain feedback control systems, contending with the effects of both noise and disturbances, quantifying uncertainty, and identifying models in real time during a flight test.

Based on the practical utility and active development in aircraft system identification demonstrated in the papers of this VC, it is clear that aircraft system identification will remain an important and extensible skill that will aid the vehicle development process in the future. A continued effort to do this with more complex and descriptive global nonlinear models can be expected, with results available faster and/or in real time, and with more efficient and effective flight tests through advances in experiment design. Cheaper high-quality sensors, such as miniature inertial measurement units and fiber-optic strain sensors, are enabling system identification of flexible structures using distributed sensing and modeling. Although there are areas related to aircraft where machine learning and artificial intelligence may be usefully applied, these approaches have yet to exhibit significant benefits for aircraft system identification, perhaps due to the continued success and practical utility of physics-based and statistical modeling techniques.

In closing, we would like to acknowledge the work of the contributors to this VC. The authors have spent significant time and effort writing and revising their work for the benefit of this VC. In addition, each paper was anonymously peer-reviewed by several other contributing authors, and the comments in general were extremely thorough and constructive. These reviews by expert colleagues were arranged to ensure the accuracy and practical applicability of the material presented in the papers. We would also like to warmly thank the former Editor-in-Chief, Dr. Eli Livne, for approving this VC and enthusiastically supporting this effort. The current Editor-in-Chief, Dr. Mark Drela, has matched this support, which is similarly appreciated. In addition, we would like to thank Karina Bustillo from the AIAA and Liz Gibson from Technica Editorial Services for their work in publishing this VC.

References

[1] Klein, V., and Morelli, E., "Aircraft System Identification: Theory and Practice," Education Series, AIAA, Reston VA, 2006.

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10 articles summarizing recent progress in aircraft system identification:

- US Army: Berger, Tobias, Tischler, and Juhasz
- NASA LaRC: Morelli and Grauer
- DLR: Deiler, Mönnich, Seher-Weiß, and Wartmann
- IPEV: Dias and Silva
- TUM: Hosseini, Steinert, Hofmann, Fang, Steffensen, Holzapfel, and Göttlicher
- TAMU: Leshikar, Valasek, and McQuinn
- Barron: Cooper, DeVore, Reed, and Morelli
- TU Delft: de Visser and Pool
- VT: Simmons, Gresham, and Woolsey
- STI: Lampton, Klyde, and Schulze

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