NASA ULI

Safe, Low-Noise Operation of UAM in Urban Canyons via Integration of Gust Outcomes and Trim Optimization

Annual Report, Year 3

Sheryl Grace, PI
Assoc. Prof. Mechanical Engineering
Boston University
617-353-7364
sgrace@bu.edu

POP for report: Year 3, 7/1/25 - 6/30/26
POP for project: 8/1/23 - 8/31/26
Submission date: if 7/2/2026
Final report: NO
Annual report: YES

Trustees of Boston University, 1 Silber Way, Boston, MA 02215-1703
UEI: THL6A6JLE1S7
EIN: 04-2103547

Award Number: 80NSSC23M0057

Executive Summary

This ULI addresses NASA's ULI Strategic Thrust 4: Safe, Quiet, and Affordable Vertical Lift Air Vehicles. The main focus of the proposed research is the development of critical knowledge and prediction methods for addressing a main barrier to the development and adoption of Urban Air Mobility (UAM): community noise. The proposed project will enable the development of validated approaches to assist with the design of safe low-noise multirotor vehicles and control strategies for operation in urban settings. The developed methods will facilitate the investigation of potential UAM vertiport locations and flight corridors. The team is made up of researchers from Boston Univ., Embry Riddle Univ., Tuskegee Univ., Virginia Tech and Joby Aviation with educational partner Univ. of Maryland Eastern Shores.

This work supports ARMD's outcome for 2025-2035: New vertical lift configurations and technologies introduced that enable new markets, increase mobility, improve accessibility, and reduce environmental impact. The proposed research targets major outcome risks by improving the aeroacoustic modeling of UAM vehicles subject to environmental disturbances guiding both their future design and operation.

Major goals and objectives

The requirements that UAM be safe like traditional aircraft, closer to carbon neutral than traditional aircraft, and provide vertical take-off and landing (VTOL) have driven designs that use multiple rotors. These vehicles come in a significant variety of configurations. A believed benefit is much quieter vehicles compared to traditional single large-rotor vehicles. However, UAM are expected to operate much closer to population centers on a more continuous basis than traditional aircraft. Furthermore, they will take off and land from rooftops that may be near other taller buildings and then fly in the urban canyon. The overarching objective of this research is to address fundamental knowledge gaps related to performance and noise that are critical for enabling UAM operation in an urban setting. To this end, the following activities are being undertaken to specifically address the following technical challenges:

Overview of accomplishments by technical challenge

$\boxed{\text{TC 1: The effect of urban flows on UAM performance and noise.}}$

This is an expansive topic that has been largely unstudied previously. This project adopts a multipronged approach for addressing fundamental knowledge building blocks that support better understanding and prediction capabilities for multirotor vehicles in urban flows. This is a summary of the inquiries in year 3.

- Urban modeling
  - Further simulation and evaluation of flow past canonical building(s) and extraction of disturbances
  - Consideration of heating (stratification) effects on flow past buildings
  - Disturbance characterization

  - Flow extraction from full city simulation for use in propeller simulations

- Experimental campaign with single Joby prop
  - Measurement of performance and noise of single propeller with disturbance generator upstream in VT's Stability Wind Tunnel
  - Continued analysis of noise sources for eVTOL propeller at different operating conditions
  - Design of multiprop apparatus

- Mid fidelity modeling
  - Further investigation of CHARM application to propeller near support arm
  - Analysis of acoustic directivity maps of BPF predicted with CHARM for multiple propeller operating conditions with comparison to experimental data
  - Analysis of noise source using beamforming with CHARM simulated data and comparison to experimental findings
  - Investigationof Joby single propeller in a wind tunnel: CHARM and OpenFOAM actuator disk method
  - Application of DUST+PSU-WOPWOP to the Joby single propeller for performance and noise prediction
  - Correction of converter code between Helios-ROAM and PSU-WOPWOP
  - Helios-ROAM Simulations of Joby prop flying through urban flow
  - Detailed investigation of UCD-Quietfly for broadband trailing edge noise associated with the Joby propeller using XFOIL and OpenFOAM airfoil data
  - Application of TU-Delft version of Amiet's broadband noise method for turbulence ingestion noise to the Joby propeller in edgewise flight
  - Initial application of time domain method for modeling turbulence ingestion noise

- High fidelity modeling
  - Further investigation of permeable FWH analysis
  - Overflow method development for prop with upstream disturbance (source model for code)
  - OpenFOAM method development for prop with upstream disturbance (source model for code)
  - LES modeling of disturbance generator (flapped foil) for comparison to experiment and for use in defining disturbances for simulations
  - Further validation to experiment - focus on noise source validation
  - Turbulence ingestion noise direct calculation and input data extraction for the model

TC 2: The effect of UAM trim state on performance and noise.

This TC requires full vehicle performance and noise assessment as well as improved methods for trim determination. Progress was made on algorithm development for use in a trim model.

- SUI quadrotor state and noise database update using CHARM.
- Machine learning algorithm finalization to utilize database for quick state prediction

TC 3: The impact of noise as a metric on UAM path planning.

Path planning and control algorithms that take into consideration noise as an additional metric do not exist, but may prove critical to gain community buy-in for UAM.

- Path planning algorithm with noise metric tested in lab using small Tello drone
- Algorithm updated to utilize ray tracing results for noise propagation

Some of the tasks are not yet completed. The project now has a one year no-cost extension.

Products

- Joby hosting 2 interns during summer of 2026 from the ULI schools
- Two 2-day workshops focused on propeller aerodynamics and quadrotor programming (November 2025 and February 2026) for high school students in The Calculus Project
- Summer workshops at BU for students in The Calculus Project and in Upward Bound

Journal Papers

- "Multi-Fidelity Assessment of eVTOL Propeller Noise in Ground-Effect Conditions," Marques,M., Golubev, B., Lyrintzis, A., International Journal of Aeroacoustics, Feb, 2026.
- "High-fidelity simulations of noise induced by time-harmonic gust interaction with eVTOL rotor Voropayev," V„ Marques, M., Maleki, A, Lyrintzis, A, Mankbadi, R., Grace, S., and Golubev, V. International Journal of Aeroacoustics, Feb, 2026.
- "Linking canyon air temperature response to energy forcing: A large-eddy simulation study of cool roof effects," E. Akinlabi, S. Grace, D. Li, submitted to ARC Geophysical Review
- "Influence of inflow turbulence on wake dynamics of a square cylinder," Maleki, A. and Grace, S. and Mankbadi, R. and Golubev, V., Journal of Fluid Mechanics, 1028:A15-1:50, 2026

Conference Papers

- "A Spectral Proper Orthogonal Decomposition Analysis of Turbulent Flow Around a High-Rise Building." Maleki, A., Golubev, V., Mankbadi, R., AIAA Aviation, 2025, AIAA Paper No. 2025-3487.
- "Rozman, A. and Grace, S., Evaluation of Urban-Flow-Informed Gusts on eVTOL Vertiport Approach Acoustics," AIAA Aviation 2025, AIAA Paper No. 2025-3003.
- "Interaction of Edgewise Transient Disturbance with a Propeller. Hua, J., Golubev, V., and Mankbadi, R. R. AIAA Aviation 2025, AIAA Paper No. 2025-3070.
- "The Interaction of a Transient Gust Flow with a Rotor," Li, Z., Hua, J., Salehian, S., Golubev, V. V., Mankbadi, R. R., AIAA Aviation, 2025, AIAA Paper No. 2025-3069.
- "Acoustic Characteristics of a Propeller Experiencing Transient Disturbances in Forward and Edgewise Flight Conditions", Chaware, S., Huang, S., Duong, T., Lundquist, R., Intaratep, N., and Alexander, W.N., AIAA Aviation 2025, AIAA Paper No. 2025-3149..
- "Numerical Simulation of Vortex Formation and Convection of Pitching Airfoils Undergoing Dynamic Stall," Salehian, S., Grace S., AIAA Paper No.2026-0524.

- “Prediction of performance and noise of a small quadrotor using CHARM,” Rozman, A., Macrae-Sadek, E., Cable, M., Gard, D., Grace, S., AIAA Paper No.2026-1479.
- “Comparative Analysis of High and Mid-Fidelity Methods for Predicting Performance and Acoustics for UAM Applications,” Voropayev, V., Ossyra, S., Lyrintzis. A., Mankbadi,R, Golubev, V. AIAA Paper No.2026-2078.
- “Turbulence Coherent Structures Above Vertiports: Insights Into Unsteady Urban Aerodynamics,” Maleki, M., Mankbadi, R., and Golubev, V. AIAA Paper No.2026-2959.
- “Study of Propeller Noise Under Edgewise and Transition Flight Conditions for Urban Air Mobility,” Hua., J., Marques, M., Golubev, V., Lyrintzis, A., and Mankbadi, R., AIAA Paper No.2026-1480.
- “Flow Interaction Between Urban Structures and Vertiport Platforms: A Large-Eddy Simulation Study,” Maleki, M., Golubev, V., VFS 2026.
- “Impact of Transient Disturbance on the Aerodynamics and Aeroacoustics of a UAM Propeller,” Chaware S., Huang, S., Duong, T., Intaratep, N., and Alexander W. N., AIAA Paper No. 2026-3252.
- “High-Fidelity Simulations of eVTOL Rotor Turbulence Ingestion Noise,” Voropayev, V., Malek, A., Ossyra,S., Mills, J., Hua, J., Marque, M., Grace, S., Lyrintzis, A., Mankbadi, R., and Golubev,V., AIAA Paper No. 2026-3599.
- “Improving Accuracy of eVTOL Rotor Noise Predictions Using a Multi-Fidelity Simulation Framework,” Bezuidenhout, D., Golubev, V., Marques, M., and Lyrintzis, A. AIAA Paper No. 2026-3293.
- “An Application of Amiet’s Model for Turbulence Ingestion to eVTOL Propellers,” Rozman, A., Piccolo, A., and Grace, S., AIAA Paper No. 2026-3600.

Theses

- “A Multi-Fidelity Approach for Improving modelling of eVTOL Rotor Noise, Daniella Beuidenhout,” MS ERAU, May 2026
- “Numerical Investigation of Rotor-Gust Acoustic Interactions using the OVERFLOW CFD Solver,” Jordan Mills, MS ERAU, May 2026
- “Mid-Fidelity Gust-Rotor Interaction Analysis,” Stanley Ossyra, MS ERAU, May 2026
- “Machine Learning for Real-World Appications: Dynmic Modeling Collision Avoidance, and Human Activity Recognition,” Xinhuan Sang, PhD, BU, May 2026

Impact

The findings related to best practices for propeller and multirotor modeling have been disseminated through conference presentations and papers as listed above. Some highlights include:

- Best practices for applying FWH permeable surface have been developed and presented to the community
- Results from the investigation of best practices for applying CHARM+PSU-WOPWOP to multirotor vehicles have been made available to the community
- Methods for introducing disturbances in high fidelity simulations via source terms have been developed and presented to the community

- Initial insights into the effect of a real urban disturbance on the performance and noise of a propeller are now available to the community

In general, the project continues to increase the knowledge base on how well mid- and high-fidelity simulation tools predict performance and noise from single propellers and multirotor vehicles.

Importantly, this year, the results from the previous year's single propeller experimental campaign have been incorporated into a benchmark challenge to be run through the NASA technical working group with findings to be presented at upcoming AIAA conferences and NASA working group meetings. As well, initial experimental data from the propeller in a transient disturbance have been made available. Integration of urban flow simulation outcomes and the simulation of a propeller operating in such a flow show promise at both mid and high fidelity and the first predictions have now been reported in the literature.

The ability for path planning to include noise as a control parameter has been demonstrated. This opens an entire new field of inquiry that brings together controls and the human perception work that has been performed at NASA.

The outreach workshops at BU and the Joby internships continue to add to work-force training in this emerging field of eVTOL.

Participants and other collaborating organizations

Name	Organization	Rank	Salary mo.	For. Collab	For. Travel
Sheryl Grace	BU	Assoc. Prof.	1.5	N	Y, ITLY
	PI				
Roberto Tron	BU	Assoc. Prof.	1.0	N	Y, ITLY
	Co-I. Controls.				
Dan Li	BU	Assoc. Prof.	2.0	N	Y, JPN, GER, CHIN
	Co-I. Urban flows.				AUST, BELG, ITLY,
Emmanuel Akinlabi	BU	Post doc	4	N	N
	Urban flows PALM				
Adam Rozman	BU	PhD Student	10.5	N	Y, ITLY
	High and mid prop sims - Helios, CHARM; BB noise.				
Idris Seidu	BU	PhD Student	10	N	N
	Path planning; JA intern				
Leo (Xinhuan) Sang	BU	PhD Student	9	N	N
	Mutirotor trim				
Nuo Li	BU	PhD Student	10.5	N	N
	Broadband noise modeling				
Vladimir Golubev	ERAU	Prof.	1	N	Y, COL, RSA, NZL, I
	Co-I. Urban & propeller sims				
Tasos Lyrintzis	ERAU	Prof.	1	N	Y, GRC, ITLY
	Co-I. Propeller sims				
Reda Mankbadi	ERAU	Prof.	1	N	N
	Co-I. Propeller sims				
Alireza Maleki	ERAU	PhD Student	12	N	N
	Urban flow sims OpenFOAM				
Jie Hua	ERAU	PhD Student	4	N	N
	High prop sims OpenFOAM				
Michael Marques-G.	ERAU	PhD Student	1	N	N
	High and mid prop sims - OpenFOAM, CHARM; BB noise				
Daniel Maleev	ERAU	MS student	0	N	N
	Prop sims overflow; JA intern				
Jordan Mills	ERAU	MS student	9	N	N
	Prop sims overflow; NASA intern				
Stanley Ossyra	ERAU	PhD student	9	N	N
	Mid prop sims DUST, FLOWUnsteady; Boeing intern				
Daniella Bezuidenhout	ERAU	MS student	0	N	Y, SAFR, BOT
	Prop BB self noise - CHARM, UCD Quietfly				
Vadim Voropayv	ERAU	PhD student	9	N	Y, FRA
	High prop sims with dist OpenFOAM; JA intern				

Name	Organization	Rank	Salary mo.	For. Collab	For. Travel
W. Nathan Alexander	VT	Assoc. Prof.	1	N	Y, ITLY
	Co-I: experiments				
Nanya Interatep	VT	Assoc. Res. Prof.	1	N	Y, ITLY
	Co-I: experiments				
Szu-Fu Huang	VT	PhD student	9.5	N	Y, ITLY
	Experiments disturbance design; JA intern				
Shreyas Satish	VT	PhD student	12	N	Y, ITLY
	Experiments PIV				
Jeremy Bain	JA	Engineer	0	N	Y, ITLY
	Co-I: Industry mentor				
Austin Thai	JA	Engineer	0	N	N
	Industry mentor, Intern director				
Lanju Mei	UMES	Assoc. Prof.	0.25	N	Y, CHIN
	Co-I: Educational partner				

- Boston University (BU)
- Embry Riddle University (ERAU)
- Virginia Polytechnic Institute and State University (VT)
- Joby Aviation (JA): Jeremy Bain, Austin Thai
- University of Maryland Eastern Shores (UMES)

The following undergraduates and master's student participated on the project on an hourly or volunteer basis: Elliot Dy, Charles Corbett, Sophia Becken, Jerry Jiang, Kyler Walbeek, Thomas Lisa, Sheppard Duvall, Shruti Ram, James White.

Contents

Accomplishments Details

At the core of this research is the development of accurate methods to predict how rotor performance and noise are impacted by the ingestion of large-scale disturbances that exist due to the urban environment. There were five main areas of focus put forward in the proposal each having a number of subtasks

- Urban flow modeling
- Experimental UAM studies
- Computational UAM studies
- Multirotor trim
- Trajectory planning

Grouping the last two under the umbrella of controls, the interaction of the tasks is visualized in Fig. 1. The accomplishments during the third in each of these research areas are discussed

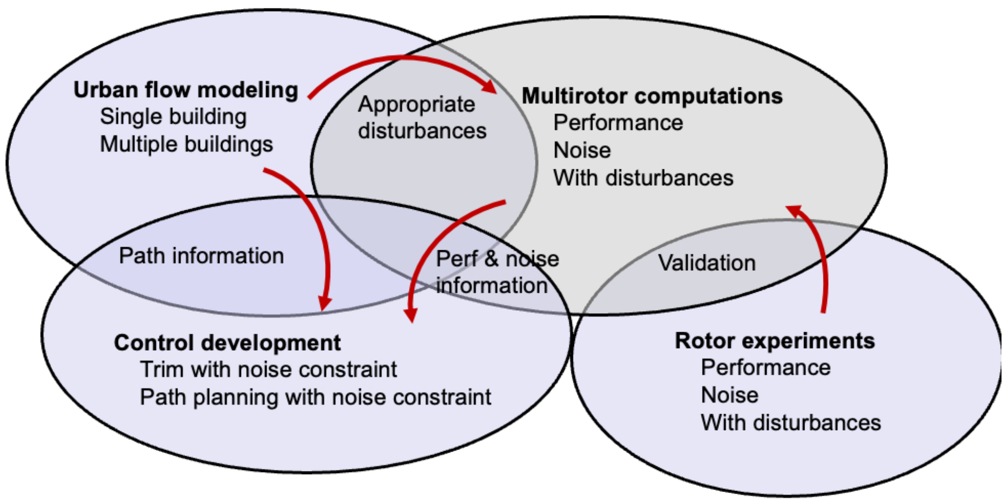

Figure 1: Project diagram with interrelated tasks.

in detail in this report. The original milestone and gantt charts for each area are reproduced from the original proposal, for comparison.

1 Urban Disturbances

Multirotor vehicles operating in urban settings are expected to take-off and land at vertiports located near buildings and thus will fly through the complex interstitial flows between buildings. As such, understanding better the flow field near buildings and how these change and how they relate to a multirotor vehicle is of interest. Five subtasks provide the framework for our work on urban flow modeling and disturbance characterization. Progress on each milestone is described below.

1.1 Detailed urban modeling

Completed in year 2[1–7].

1.2 Urban flow parameter study

In addition to parameters studied in previous years[7,8], this year the effect of stratification was also considered. When heating is allowed along surfaces of two buildings and the ground between the buildings, circulating cells between the buildings and a thermal boundary layer above the building form. These affect the local flow conditions. The results have been summarized in the paper submitted to the Journal of Geophysical Research[9].

1.3 Realistic urban modeling

PALM was used to complete an urban flow simulation for Boston. The Boston building configuration was available from 2018. 1m resolution near the two buildings that were identified as potential vertiports was obtained. The simulation was used to pull the flow field near one of the identified vertiports at both high wind and low wind times of day. One time was already used to obtain inputs for a propeller simulation. These are addressed below.

OpenFOAM was used to simulate the flow near one tall building under reasonable wind conditions. The unsteady flow field near the top of the building was extracted and is also being used to set the upstream disturbance in a propeller simulation[10]. During the no-cost extension, a simulation of the New York based vertiports that were used during the Joby flights this year, may be completed to help post process data from those flights.

1.4 Disturbance characterization and modeling

The SPOD completed in year 1 highlighted various disturbance types[3]. Disturbances have also been considered using FFT analysis and time domain analyses in preparation for use with the rotor simulations. The original thought that the disturbances must be characterized in terms of canonical gusts is no longer a main goal. It has been determined that having the disturbance defined in time couples to the simulations better. As such, this is being pursued now. Further analysis of the flow field continues in order to support its description as a source term for high fidelity simulations.

1.5 Disturbance coupling to rotor simulations

Disturbance coupling is a main focus of the propeller simulations now. Early simulations of the propeller and an upstream flapped airfoil[11–14] preceded the actual experimental campaign. It was determined that both for flexibility and for computational savings, methods for including disturbances upstream of a propeller via a source term that can be introduced very close to the propeller as opposed to at an upstream boundary is of great interest. Methods for introducing the source term such that the simulations remain stable and physical are being developed for OpenFOAM, Overflow and Helios (Overflow and ROAM), DUST and CHARM. Initial results for all cases exist, but more work is being done to ensure the simulations are truly physical.

In year 2, DUST and OpenFOAM[15,16] were used to model a single frequency disturbance interacting with a propeller. The results fell in line with historic work that showed this should lead to additional tones on either side of the blade pass frequency and its harmonics. The influence on thrust and torque was negligible. Consideration of a periodic disturbance was interesting but the main focus is transient disturbances.

Two main transient disturbance types are being considered:

- the flapped airfoil wake
- the flow near the top of a building

The flapped airfoil was simulated using DDES in OpenFOAM as part of the early coupled simulations[11,14]. More recently, just the flap was simulated using OpenFOAM but with overset grids. Different turbulence modeling methods were considered including LES, DDES, and URANS[17]. The results were compared to experimental values and it was determined that a) OpenFOAM with overset grids does not allow for accurate DDES; and b) the URANS gives results that are easily compared to the experimentally measured deterministic part of the flow. The interest in the LES simulation stems from its ability to provide full 3D space - time flow information on which a source term can be based. The experimental data is confined to only a few PIV planes. As such these simulations not only serve as a validation of the OpenFOAM capabilities in terms of it's turbulence models when using overset grids but also as support for the propeller simulations.

The first simulation of the influence of a realistic urban flow on the noise from a propeller was performed in year two[18]. The Boston Beech St. vertiport flow field obtained from PALM provided the realistic flow. A landing trajectory based on FAA vertiport rules for an 8:1 approach path was set. The flow field was probed along this path over a time that corresponded to an approach speed of 22 m/s. The urban flow database was probed at the location of the center of the single propeller during the decent. The entire flow field around the propeller was then adjusted in time based on this probed data. The mid-fidelity Helios-ROAM was used for these simulations. In year 3, it was discovered that the converter code between ROAM and PSU-WOPWOP was not working properly. It has been updated and corrected and now the noise for that first case is being reassessed. In addition, methods for pulling 2D flow data along a flight path and introducing it into a Helios-ROAM simulation are being developed. Finally, decent of the full Joby vehicle which has six propellers is being considered and the flow at the center of each propeller along the descent path has been pulled from the urban flow simulation. During the no-cost extension, this data will be used by Joby to test their control algorithms.

The urban flow simulation task is hitting its milestones but a bit later than originally estimated. The no-cost will enable the final analyses to be completed. The simulation methods have been validated and verified; disturbance types of interest near buildings have been identified; the effect of some parameters such as Reynolds number and atmospheric turbulence levels have been quantified; preliminary study of the effect of stratification (thermal loading) has begun; extraction of realistic flows for use with propeller simulations has been demonstrated. The final outcomes for prediction of performance and noise of propellers in a disturbed flow field will be obtained in the near future.

Table 1: Milestones and Deliverables for Task 1

Milestone/Subtask /TC/Start-End	Description (Dependency)	Exit Criteria	Deliverables
M1.1/Task 1.1 TC 1/ Q1-4	Detailed urban modeling	Validated urban benchmark completed at high resolution	Simplified urban model configuration (grid), test results, documentation
M1.2/Task 1.2 TC 1,3/Q3-8	Urban flow parameter study (M1.1)	Verification of trends based on wind speed and direction; building config.; stratification	Database of urban simulations for different conditions, documentation
M1.3/Task 1.3 TC 1,2,3/Q9-12	Realistic urban modeling (M1.1,2)	Complete Boston based simulation with 0.1m resolution	Boston flow simulation results (grid, output files) Documentation
M1.4/Task 1.4 TC 1 /Q1-12	Disturbance characterization & modeling (M1.1,2;M2.1)	Disturbances from sims and experiment mapped onto canonical disturbances, scaling	Weighted listing of disturbance types and relevant parameters for describing urban flows
M1.5/Task 1.5 TC 1,2,3/ Q2-5	Disturbances coupled to rotor simulations (M1.4;M3.1,2)	Successful demonstration of stable runs	Example response of rotor to canonical disturbances, documentation of coupling methods

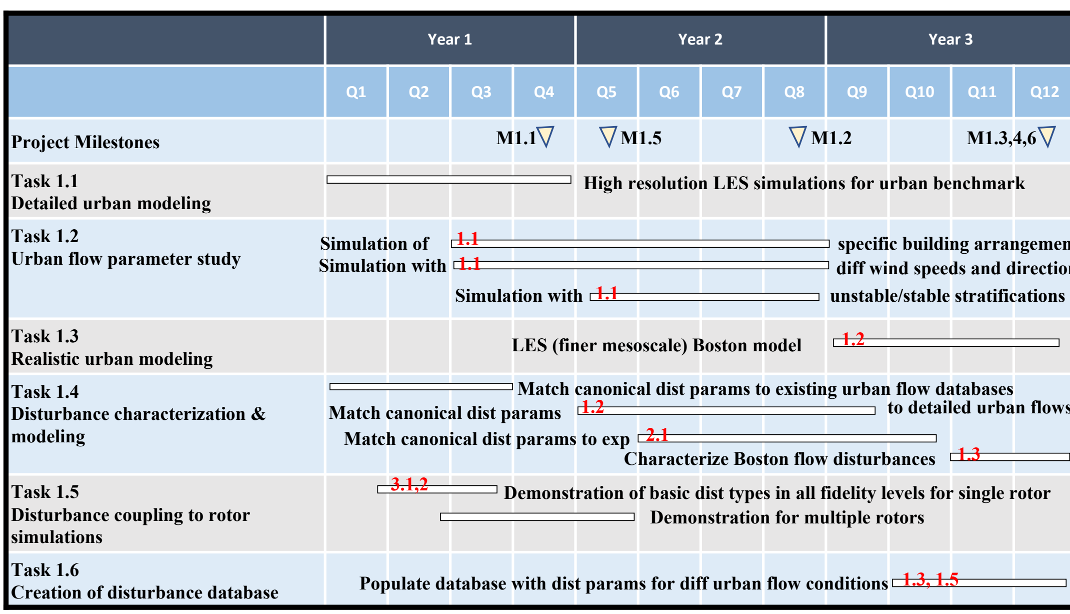

Figure 2: Task 1 schedule. Red indicates required tasks.

2 Experimental UAM studies

Significant progress has been made experimentally in this research program.

2.1 Selection of propeller geometry and baseline experiments

This was completed previously[19–21].

2.2 Characterization and matching of disturbance generator flow

The disturbance generator, flapped airfoil, was fabricated and first tested in year 2 in the Subsonic Modular Anechoic Research Tunnel (SMART) at Virginia Tech[22]. In year 3, it was installed in the Stability Wind Tunnel (SWT) and further tested[23].

The disturbance generator is a NACA 0021 airfoil with span of 1.83 m and chord of 0.15 m. It is constructed of carbon fiber sheet layups over a foam core. The carbon fiber skin has a total thickness of 0.2 mm, comprising two layers of 0.1 mm carbon fiber sheets bonded with epoxy. The actuation of a 20° motion is done at different rates in the different experiments: 150°/s and 350°/s in the SMART; and 800°/s in the SWT. The initial analysis is reported in[23]. Currently, the PIV measurements downstream of the disturbance generator are being compared to URANS and LES. As mentioned above, the comparison of the deterministic part of the flow field is good. Further thought is necessary in order to determine how to use the LES to obtain the probablistic portion.

2.3 SWT measurements of single rotors subject to disturbances

The first experiment in the SMART tunnel with a small APC propeller behind the disturbance generator (flapped airfoil) were discussed in[22]. In the third year, the disturbance generator was run in the SWT upstream of the Joby propeller. Initial results from that experiment are discussed in[23].

Many propeller conditions were run and PIV data on several planes were obtained together with microphone array measurements. A particularly interesting condition was identified by the experimentalists and currently this condition is being simulated with both high and mid fidelity codes. Comparisons of the wake position in relation to the rotor and how this changes when the disturbance generator is actuated will be completed during the no-cost extension.

2.4 SWT measurements of multirotor configurations with different trim conditions

This task is under review. In discussions with Joby, it was determined that two propellers will be used in order to highlight important interactions that may occur on landing or takeoff. As such, trim doesn't really have a defined meaning. this subtask is being morphed simply into the measurement of the two center propellers from the Joby geometry at different landing tilt angles and descent speeds.

2.5 SWT measurements of multirotor vehicles subject to disturbances

The multirotor platform is now designed. During the no-cost extenion, the experiments will be run. The same disturbance genertor will be used upstream of the two propeller configurations noted in subtask 2.4.

This task's timeline was modified due to the renovations of the stability wind tunnel (SWT). The addition of the SMART experiments using the disturbance generator upstream of an APC prop was added to the project. Propeller-disturbance performance and noise data are now available for the single Joby propeller. The disturbance flow field is well characterized. In addition, PIV of the propeller wake with and without the disturbance when in a tilted condition is allowing for further validation of the high and mid fidelity simulations. The multirotor platform is almost fully designed and will be available for deployment in the SWT soon.

Table 2: Milestones and Deliverables for Task 2

Milestone/Subtask /TC/Start-End	Description (Dependency)	Exit Criteria	Deliverables
M2.1/Task 2.1 TC 1,3/ Q1-4	Characterization & matching of disturbance generator flow (M1.4;M3.1,2,3;M4.1)	Aerodynamic and acoustic measurements of disturbances	Time-resolved data of disturbance for comparison with urban flow simulations and computational models
M2.2/Task 2.2 TC 1,2/Q1-2	Selection of UAM rotor geometry (M3.1,2,3;M4.1)	Agreement on rotor configurations by proposal team and NASA POC	Detailed propeller characteristics necessary for fabrication
M2.3/Task 2.3 TC 1/ Q2-6	SWT perf. and noise measurements of single rotors subject to disturbances (M1.4;M3.1,2)	Acquisition and analysis of perf and noise data for single rotor configurations subject to a family of disturbances	Thrust and torque. Unsteady velocity near the rotor showing interaction with disturbances and noise measurements at multiple observer locations.
M2.4/Task 2.4 TC 2,3/Q3-9	SWT perf and noise measurement of multirotor with diff trim conditions (M4.1)	Acquisition and analysis of perf and noise data for multirotor configurations at diff trim settings	Acoustic measurements and individual rotor perf data as well as unsteady velocity into downstream rotors
M2.5/Task 2.5 TC 1,2/Q8-10	SWT perf and noise measurement of multirotor subject to disturbances (M3.3;M4.1,2)	Acquisition and analysis of perf and noise data for multirotor configurations interacting with a family of disturbances	Unsteady velocity measurements of disturbances as they interact with the rotors and their effect on the rotor wakes as well as noise at multiple observer locations. Individual rotor perf.

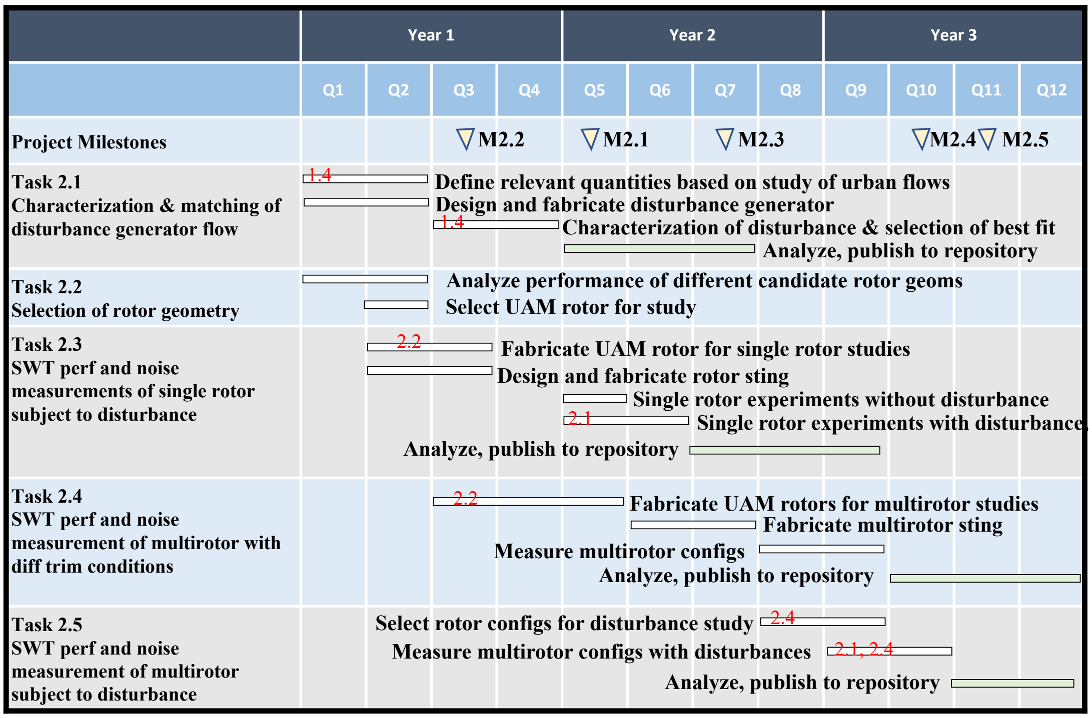

Figure 3: Task 2 schedule. Milestones set at completion of experimental campaigns. Red indicates required tasks.

3 Computational UAM studies

A main focus of this work is accurate computational prediction of multirotor performance and noise. First though single propeller analysis is required. Several tasks were the focus of years 1 and 2; however, the group continues to analyze some aspects of the single propeller simulation capabilities. Year 3 was mainly focused on developing models for broadband noise that must accompany mid fidelity simulations and simulation of disturbances upstream of propellers. Further multipropeller simulations will be considered during the no-cost extension.

3.1 Validation of high fidelity simulations

This topic is discussed in[24–28] In year 3, the data produced by high fidelity simulations were used for beam forming and the results compared to those from the experiments. These comparisons brought up several questions which will be answered during the no-cost extension.

3.2 Verification and validation of mid and low fidelity simulations

CHARM has been considered for both single propeller and multipropeller situations[26,27,29]. DUST was used and is discussed in some papers[16,28]. However, it has recently been verified more fully for the single Joby propeller. Fig.4 shows the performance results for an edgewise flow case as compared to the experimental results. Fig.4 shows the acoustic prediction of the blade pass frequency. The acoustic prediction workflow is still being checked as the result does not yet look correct.

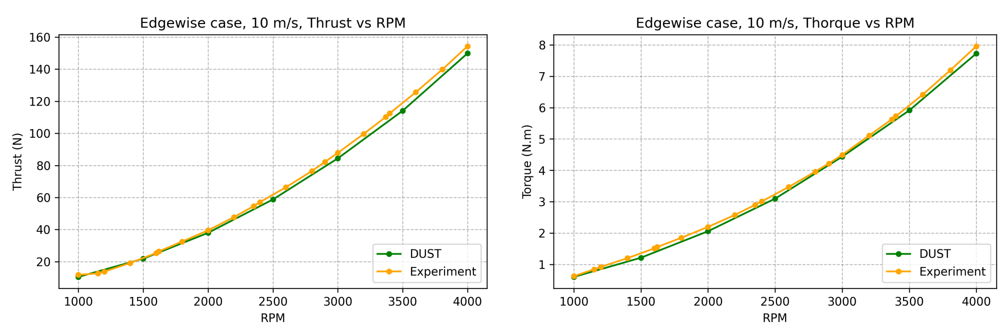

Figure 4: Joby propeller performance prediction with DUST. Edgewise flow 20 m/s. DUST run using 17.5 deg collective instead of 16 deg.

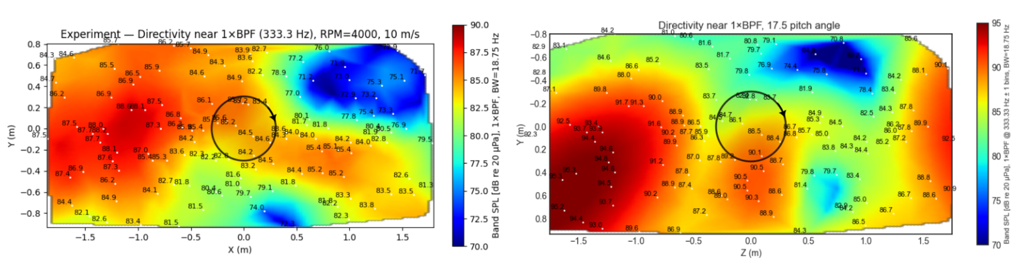

Figure 5: Joby propeller acoustic prediction with DUST. Edgewise flow 20 m/s. DUST run using 17.5 deg collective instead of 16 deg. BPF.

Helios-ROAM and CHARM were benchmarked against each other. It was determined that the coupling between ROAM and PSU-WOPWOP was incorrect. The converter was updated and the ROAM acoustic results now work well and compare well against CHARM results. Further work is now being done with ROAM and CHARM where multiple microphone arrays are being used to surround the propeller. Beam forming is then being used with all of the arrays to help better understand the beamforming capability and importance of the actual source directivity in the current setting.

3.2.1 Broadband Modeling

Trailing edge broadband noise modeling with UCD-Quietfly has been applied to the Joby propeller with input taken from both XFOIL and CFD analyses of 2D airfoils with CHARM inflow quantities specified[26,30–32].

The focus now is turbulence ingestion noise (TIN). A model based on Amiet's approach that has been adapted by researchers at TU Delft was initially adopted. The results for a perfectly edgewise single propeller case are presented in[33]. The turbulent inflow quantities were obtained in two ways for the study. 1) The high fidelity simulation was probed and the velocity was taken directly from the simulation. 2) The turbulence was modeled based on turbulence statistics. The turbulence statistics were obtained from time accurate velocity data taken from the high fidelity simulation and from the turbulence model parameters from ROAM. This required ROAM to be updated so that the 2-equation turbulence model could be run for the cases of interest. It was determined that the edgewise case cannot be simulated using input taken from ROAM because the flow is totally separated on the retreating blade side and this is not modeled well with ROAM. Currently, a different propeller tilt angle is being considered so as to minimize this separated flow issue and allow for comparison between Overflow and ROAM based input data. In addition, during the no-cost extension, the use of a time-domain based broadband method will be considered. This method is used regularly by the experimentalists but hasn't been used with the high fidelity data previously.

3.3 Simulation of disturbance interaction with multirotors

This was described in detailed in Section 1.5. The difficult problem of predicting performance and noise when a propeller interacts with a larger scale transient flow disturbance is being addressed. Harmonic and homogeneous turbulent disturbances are also being addressed. Methods for introducing disturbances in the high fidelity simulations via source terms is almost fully vetted. The process for introducing the disturbances into the mid-fidelity methods of CHARM and DUST is just getting under way. The mid-fidelity Helios-ROAM solver is currently being run with two-dimensional unsteady inflow specified over an entire vehicle flight trajectory.

> The task is slightly behind in that multiple rotors in disturbed flow has not yet been addressed computationally. Many best practices for running high and mid fidelity simulations for propellers (when non-hover cases and noise are of interest) have been determined. The introduction of disturbances has been changed to focus on time based source terms and will be continued during the no-cost extension.

Table 3: Milestones and Deliverables for Task 3

Milestone/Subtask /TC/Start-End	Description (Dependency)	Exit Criteria	Deliverables
M3.1/Task 3.1 TC 1,2,3/Q1-5	Validation of high fidelity (M2.3)	Performance to within 5% and noise to within 3dB for tonal and 3 dB OASPL compared to data	Validation test cases and simulation results
M3.2/Task 3.2 TC 1,2,3/Q1-9	Validation of mid and low fidelity (M2.3)	Performance to within 10% and noise to within 3dB for tonal and 3 dB OASPL compared to data	Validation test cases and simulation results
M3.3/Task 3.3 TC 1/Q3-10	Disturbance interaction with multirotors (M1.3,4; M2.4;M3.1,2)	Performance to within 5% and noise to within 3dB for tonal and 3 dB OASPL compared to data	Validation test cases and simulation results

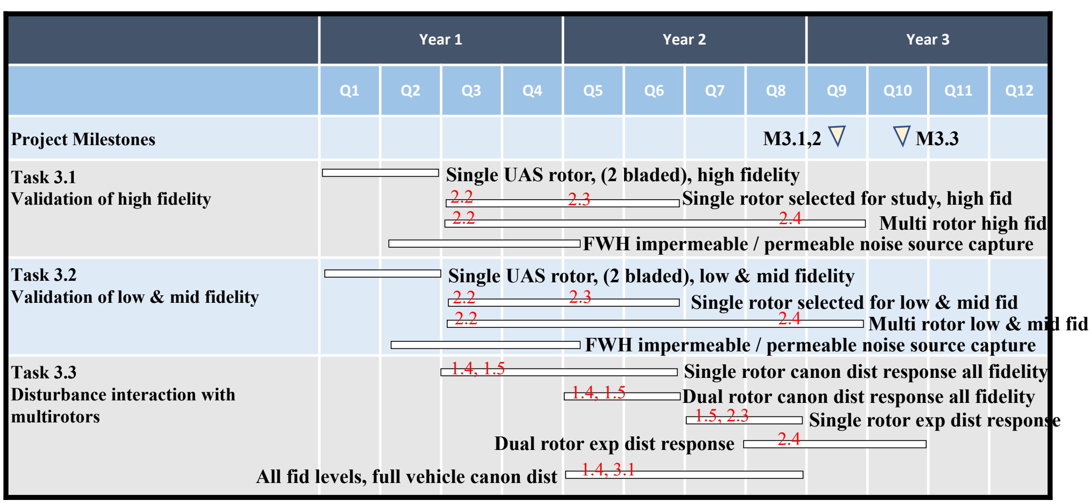

Figure 6: Task 3 schedule. Red indicates required tasks..

4 Multirotor trim prediction

4.1 Trim in unsteady setting

The propeller simulation group did attempt some trim studies that were building blocks to understanding what trim can mean in a maneuvering or disturbed flow setting. Much more has to be done to understand this situation better and to identify realistic trim settings. This will be a focus during the no-cost extension.

4.2 Controller for trim optimization given multiple DOF

An updated performance and noise database was created using CHARM for the SUI drone. This database included the SPL of the sum of the first 10 tones at 3 observers fixed in a global reference frame. The force and moment vectors were also recorded as well as the Jacobian for how these parameters are affected by the main control inputs of propeller RPM and vehicle pitch, roll and yaw. As the parameter space is very large, a Latin Hypercube method for sampling the space was used. An algorithm to learn basic rules from the database was then contructed. A controller that used a Gaussian Process informed by the database was tested[34]. It was shown to work although it was not as good as the default controller. The ability to machine learn the noise values was also demonstrated, but in this part of the project the noise values were not used. The research demonstrated that the necessary surrogate models can be developed to be used in a trim module.

The trim goals for this research are being modified slightly. Data from the urban flow simulations are being transmitted to Joby. They will exercise their control algorithms on the simulated urban flow data. They will assess how sensitive their controller is to the flow disturbances. Noise will not be included in this test. During the no-cost extension, we do hope to address setting trim conditions based on noise metrics.

Table 4: Milestones and Deliverables for Task 4

Milestone/Subtask /TC/Start-End	Description (Dependency)	Exit Criteria	Deliverables
M4.1/Task 4.1 TC 2,3/ Q3-11	Trim in unsteady setting (M2.4,5;M3.3)	Verification across fidelities. Validation within 2% on RPM and 2° on pitch and associated noise to within 3dB OASPL	Verification tests, Validation tests, Insights into effect of trim inclusion on disturbance response
M4.2/Taks 4.2 TC 2,3 / Q6-9	Trim optimizer based on noise metrics (M2.4;M3.2,3)	Demonstrate trim optimization with multiple DOF	Optimization method with newly defined constraints for multi DOF trim

5 Safe trajectory planning for UAM

While obstacle avoidance and following reference trajectories are common in path planning, the addition of noise as a constraint represents a new challenge in the field. A new path planning method is being developed.

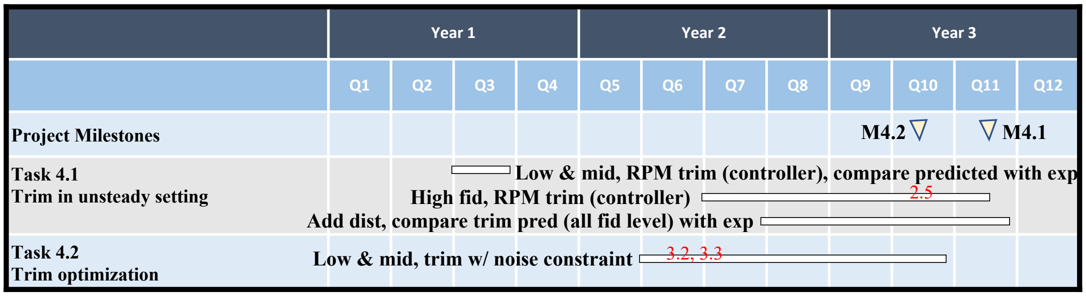

Figure 7: Task 4 schedule. Red indicates required tasks.

5.1 Path planning algorithm

The basic algorithm was develoed in year 2[35].

5.2 Path planning with and without urban flow

Experiments showed that the algorithm works to get a small Tello drone through a few scaled buildings to a destination beyond the buildings. A noise criterion could be added to the algorithm that forced an adjustment of the drone's movement so as to minimize the accumulated noise at a microphone in the lab. Fans were not utilized in these experiments to simulate the case when there is urban flow. It turns out that this effect was already considered in a PhD dissertation joint between NASA Ames and the University of Pennsylvania. Application of findings from that research together with the noise aware path planning algorithm being developed will be used to complete this subtask.

A method for including the scattering of sound emitted by the drone from nearby buildings was attempted. Full implementation of this will happen during the no-cost extension.

Path planning for an aerial vehicle that includes noise and obstacle avoidance has been demonstrated in simulation and in the lab with a small quadrotor. A more complicated model for the vehicle noise based on computed noise spheres will now be used to create the Control Barrier Function (CBF). Ray tracing to include the effect of wave reflection off of buildings is also be employed to further inform the CBF.

Table 5: Milestones and Deliverables for Task 4

Milestone/Subtask /TC/Start-End	Description (Dependency)	Exit Criteria	Deliverables
M5.1/Task 5.1 TC 3/Q5-8	Extend controller (M4.1)	Demonstrate cumulative and area constraints	Improved CLF-CBF algorithm
M5.2/Task 5.2 TC 3/Q4-8	Path planning algorithm (M3.3)	Demonstrate simulation of diff path outcomes due to diff noise constraints	Extended RRT* algorithm
M5.3/Task 5.3 TC 3/Q8-12	Path planning w/ & w/o urban flow (M1.3;M3.3;M4.3)	Demonstrate path planning through Boston model	Simulation results. Method details.

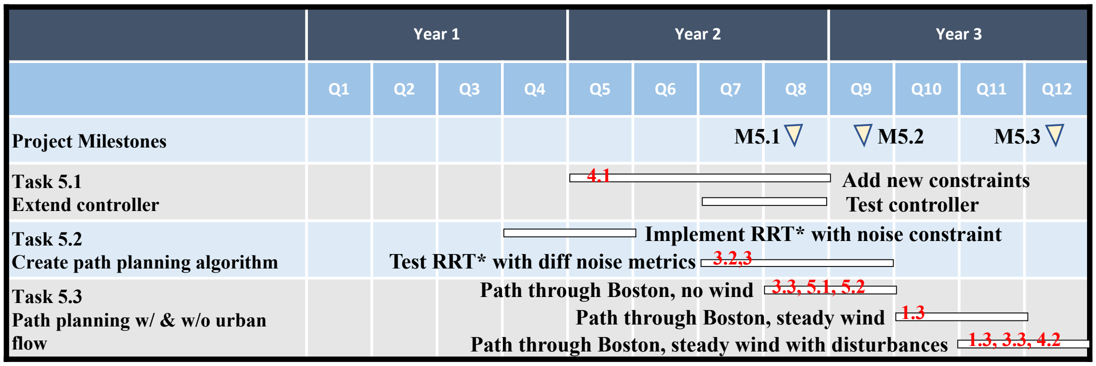

Figure 8: Task 5 schedule. Red indicates required tasks.

Education/workforce development

Beyond the involvement of many undergraduate and graduate students in the research, outreach workshops with The Calculus Project (TCP) and Upward Bound were developed and run during the 3rd year. Both of these programs target middle and high school students in the greater Boston area. 25 TCP students took part in a 2-day workshop in November. The success led to the running of a second 2-day workshop in late January with another 25 students. Over the summer, 2 more 2-day TCP workshops will be conducted and one modified 3-day upward bound workshop. In the workshops, the students explore basic aerodynamics and propeller performance. They program Tello education quadrotors and take part in various challenges with the drones.

Joby is hosting two interns affiliated with the NASA ULI program during the summer of 2026:

- Vadim Voropayev(PhD, ERAU) – CFD intern.
- Steve Huang (PhD, VT) – Testing Intern.

References

[1] A. Maleki, B. Ahmed, S. Singh, and V. Golubev. High-fidelity analysis of unsteady flow characteristics around vertiport model. In AIAA SCITECH, January 2024. AIAA Paper No. 2024-2550.

[2] Alireza Maleki, Surabhi Singh, and Vladimir Golubev. High-fidelity analysis of synthetic turbulence effects on vertiport unsteady flow characteristics. In AIAA SCITECH, 2025. AIAA Paper No. 2024-2550.

[3] Alireza Maleki, Reda R. Mankbadi, and Vladimir Golubev. Spectral proper orthogonal decomposition analysis of coherent vortical structures in the wake of a rectangular cylinder. Physics of Fluids, 37(4), 2025.

[4] A. Maleki, V. Golubev, and R. Mankbadi. A spectral proper orthogonal decomposition analysis of turbulent flow around a high-rise building. In AIAA Aviation, 2025. AIAA Paper No. 2025-3487.

[5] Alireza Maleki, Sheryl Grace, Reda R. Mankbadi, and Vladimir Golubev. Influence of inflow turbulence on wake dynamics of a square cylinder. Journal of Fluid Mechanics, 1028:A15–1:50, 2026.

[6] M. Maleki, R. Mankbadi, and V. Golubev. Turbulence coherent structures above vertiports: Insights into unsteady urban aerodynamics. In AIAA SciTech, 2026. AIAA Paper No. 2026-2959.

[7] E. O. Akinlabi, A. Maleki, V. Golubev, S. Grace, and D. Li. Flow structures near a tall urban air mobility vertiport: A large-eddy simulation study. Journal of Wind Engineering and Industrial Aerodynamics, 2025. Under review.

[8] M. Maleki, R. Mankbadi, and V. Golubev. A numerical study of synthetic turbulence interaction with unsteady vertiport environment. In VFS 81, 2025.

[9] E. Akinlabi, S. Grace, and D. Li. Linking canyon air temperature response to energy forcing: A large-eddy simulation study of cool roof effects. ARC Geophysical Review, 2026. Submitted.

[10] M. Maleki and V. Golubev. Flow interaction between urban structures and vertiport platforms: A large-eddy simulation study. In VFS 82, 2026.

[11] J. Hua, S. O. Afari, V. Golubev, and R. R. Mankbadi. Wake interaction with a propeller of an urban air mobility. AIAA Journal, pages 1–15, 2025.

[12] J. Hua, V. Golubev, and R. R. Mankbadi. Interaction of edgewise transient disturbance with a propeller. In AIAA Aviation, 2025. AIAA Paper No. 2025-3070.

[13] Zhuorui Li. The interaction of a transient forward axial disturbance flow with a rotor. Master's thesis, Embry-Riddle Aeronautical University, 2025.

[14] Z. Li, J. Hua, S. Salehian, V. V. Golubev, and R. R. Mankbadi. The interaction of a transient gust flow with a rotor. In AIAA Aviation, 2025. AIAA Paper No. 2025-3069.

[15] V. Voropayev, M. Marques, A. Maleki, A. Lyrintzis, R. Mankbadi, S. Grace, and V. Golubev. High-fidelity simulations of noise induced by time-harmonic gust interaction with eVTOL rotor. International Journal of Aeroacoustics, February 2026.

[16] Stanley Ossyra. Mid-fidelity gust-rotor interaction analysis. Master's thesis, Embry-Riddle Aeronautical University, May 2026.

[17] N. Li, S. Salehian, and S. Grace. Numerical simulation of vortex formation and convection of pitching airfoils undergoing dynamic stall. In AIAA SciTech, 2026. AIAA Paper No. 2026-0524.

[18] A. Rozman and S. Grace. Evaluation of urban-flow-informed gusts on eVTOL vertiport approach acoustics. In AIAA Aviation, 2025. AIAA Paper No. 2025-3003.

[19] Nathan Alexander. NASA ULI experimental findings: Aeroacoustics wind tunnel working session presentation. In Aeroacoustics, Rome, Italy, June 2024.

[20] Ryan D. Lundquist. Investigation of the aerodynamic and acoustic performance of a scaled eVTOL propeller in axial and non-axial flight. Master's thesis, Virginia Tech, 2025.

[21] S. Huang, S. Chaware, R. Lundquist, N. Intaratep, and W. N. Alexander. Noise of a propeller designed for eVTOL operations in forward and edgewise flight. In VFS Forum 81, 2025.

[22] S. Chaware, S. Huang, T. Duong, R. Lundquist, N. Intaratep, and W. N. Alexander. Acoustic characteristics of a propeller experiencing transient disturbances in forward and edgewise flight conditions. In AIAA Aviation, 2025. AIAA Paper No. 2025-3149.

[23] S. Chaware, S. Huang, T. Duong, N. Intaratep, and W. N. Alexander. Impact of transient disturbance on the aerodynamics and aeroacoustics of a UAM propeller. In AIAA SciTech, 2026. AIAA Paper No. 2026-3252.

[24] Adam Rozman. Evaluating the permeable surface approach for wing-propeller aeroacoustics using high-fidelity CFD. In Vertical Flight Society, Transformative Vertical Flight, Santa Cruz, CA, 2024.

[25] J. Hua, V. Golubev, S. Grace, A. Lyrintzis, and R. Mankbadi. Investigation of noise prediction for a five-bladed propeller under edgewise flow using permeable Ffowcs Williams and Hawkings surfaces. Physics of Fluids, 2025.

[26] Michael Marques G. Aeroacoustic Applications to Jets and Rotors. PhD thesis, Embry-Riddle Aeronautical University, 2025.

[27] M. Marques, B. Golubev, and A. Lyrintzis. Multi-fidelity assessment of eVTOL propeller noise in ground-effect conditions. International Journal of Aeroacoustics, February 2026.

[28] V. Voropayev, S. Ossyra, A. Lyrintzis, R. Mankbadi, and V. Golubev. Comparative analysis of high and mid-fidelity methods for predicting performance and acoustics for UAM applications. In AIAA SciTech, 2026. AIAA Paper No. 2026-2078.

[29] A. Rozman, E. Macrae-Sadek, M. Cable, D. Gard, and S. Grace. Prediction of performance and noise of a small quadrotor using CHARM. In AIAA SciTech, 2026. AIAA Paper No. 2026-1479.

[30] D. Bezuidenhout, V. Golubev, M. Marques, and A. Lyrintzis. Improving accuracy of eVTOL rotor noise predictions using a multi-fidelity simulation framework. In AIAA SciTech, 2026. AIAA Paper No. 2026-3293.

[31] Daniella Beuidenhout. A multi-fidelity approach for improving modelling of eVTOL rotor noise. Master's thesis, Embry-Riddle Aeronautical University, May 2026.

[32] D. Bezuidenhout, M. Marques, V. Golubev, and A. Lyrintzis. A multi-fidelity approach for improving modelling of evtol rotor noise. In VFS 82, 2026. VFS.

[33] A. Rozman, A. Piccolo, and S. Grace. An application of Amiet's model for turbulence ingestion to eVTOL propellers. In AIAA SciTech, 2026. AIAA Paper No. 2026-3600.

[34] Xinhuan Sang. Machine Learning for Real-World Applications: Dynamic Modeling Collision Avoidance, and Human Activity Recognition. PhD thesis, Boston University, May 2026.

[35] Idris Seidu and Roberto Tron. Navigating the noise: A CBF approach for nonlinear control with integral constraints. In IEEE Conference on Decision and Control, 2024.