Project 077 Measurements to Support Noise Certification for UAS and UAM Vehicles and Identify Noise Reduction Opportunities

The Pennsylvania State University

Project Lead Investigator

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University Participants

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- P.I.: Eric Greenwood, Assistant Professor of Aerospace Engineering
- FAA Award Number: 13-C-AJFE-PSU-112
- Period of Performance: March 15, 2024, to September 30, 2026
- Tasks:
  1. Computational predictions of unmanned aircraft system (UAS) noise
  2. Microphone array design using computational modeling
  3. Development and testing of a reconfigurable multirotor UAS
  4. UAS noise measurement and analysis
  5. Development of a source separation process (SSP) for distributed propulsion vehicles
  6. Noise reduction through synchrophasing
  7. Improved air-data system integration and calibration

Project Funding Level

The Federal Aviation Administration (FAA) provided $500,000 in funding. Cost sharing funds of $495,933 were received from Beta Technologies for labor, flight test support, and technical data.

Investigation Team

Eric Greenwood (P.I.), All Tasks
Kenneth S. Brentner (co-P.I.), Tasks 1, 2 and 7
Eric N. Johnson (co-P.I.), Tasks 2 and 5
Vítor T. Valente (senior personnel), Tasks 2, 3, 4, 6, and 7
Joel Rachaprolu (graduate research assistant), Tasks 4, 5, and 7
Rupak Chaudhary (graduate research assistant), Tasks 1, 2, 4, 6 and 7
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Project Overview

Measurement techniques for conventional propeller-driven aircraft and rotorcraft are well established. These techniques typically assume that the acoustic state of the vehicle does not change over the duration of a steady-state pass over a microphone or microphone array. UAS and urban air mobility (UAM) platforms violate the steadiness assumption used in the measurement and modeling of conventional aircraft noise. Rotor or propeller states, such as the rotational speed or blade pitch angle, vary continuously and independently as the vehicle control system responds to atmospheric perturbations. Many of these vehicles use distributed propulsion systems, in which the rotors or propellers are not locked in phase. When multiple rotors or propellers operate at similar blade passing frequencies, coherent addition of the tonal noise results in lobes of acoustic radiation that are tightly focused in certain directions. As the phase relationships between the rotors change over time, the directionality of these lobes varies. Consequently, the noise cannot be modeled as a single stationary source, and no two flight passes will result in the same noise radiation pattern on the ground. Moreover, because numerous possible combinations of control inputs can result in the same flight condition, unique mapping of the overall flight condition of the vehicle to a corresponding acoustic state is no longer present. This project is aimed at developing noise measurement techniques and data analysis methods that can reduce this variability, thereby allowing for repeatable characterization of UAS and UAM noise.

Task 1 – Computational Predictions of UAS Noise

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Objectives

The objective of this task is to understand the noise characteristics of small multirotor vehicles in hover and level flight and to support the field measurement planning, testing method development and noise data collection. The task focuses on the X8 UAS configuration developed during the previous year of this project. The X8 configuration has four rotor support arms, each of which supports two rotors driven by separate electric motors in a coaxial arrangement. This octocopter configuration is commonly used in modern drones and relevant to applications such as package delivery. The rotors on each arm may be operated in either co- or counter-rotating pairs. Another objective of this task is to evaluate the acoustic characteristics of Penn State's X8 octocopter when operating in either co- or counter-rotating configurations prior to acoustic measurements in the field.

Research Approach

The Penn State Noise Prediction System (NPS) was used to predict the noise characteristics of co- and counter-rotating octocopter configurations. Although flight acoustic measurements have not yet been performed for these configurations, these predictions are being used to guide the design of future experimental maneuvers. Since experimental data for the X8 are not yet available, the simulation approach was validated against previously collected acoustic measurements of similar co- and counter- rotating rotors pairs obtained in Penn State's flow through anechoic chamber under a separate National Aeronautics and Space Administration (NASA)-supported project.

Milestones

- Model the co- and counter-rotating octocopter configurations in the Penn State NPS.
- Validate the predicted noise using previously obtained measurements of coaxial rotor acoustics.
- Use the noise predictions to study the noise characteristics of each configuration and inform the design of future experimental procedures.

Major Accomplishments

A model of the large reconfigurable UAS X8 has been developed by using the Penn State NPS. The NPS, described by Figure 1, is a simulation architecture consisting of three subsystems: (1) PSU Distributed Electric Propulsion Simulator (PSUDEPSim), (2) the Comprehensive Hierarchical Aeromechanics Rotorcraft Model (CHARM), and (3) PSU-WOPWOP. PSUDEPSim is a flight simulation model for multirotor aircraft developed at Penn State. PSUDEPSim is used to compute the aircraft's flight state as it undergoes steady or maneuvering flight. PSUDEPSim can be coupled to a higher-fidelity aerodynamics model to capture the effects of interactions among components of the aircraft, such as the rotors. In the Penn State NPS, PSUDEPSim is coupled with CHARM to form DEPSim. CHARM, developed by Continuum Dynamics, Inc., is a rotorcraft comprehensive analysis platform including a higher-order free vortex rotor wake method and a panel method for aerodynamic bodies and surfaces, such as the fuselage and wings of UAM aircraft. In addition to providing aerodynamic data in DEPSim for flight dynamic simulation, CHARM produces high-resolution rotor airloads for input into aeroacoustic propagation tools, such as PSU-WOPWOP. PSU-WOPWOP is a general-purpose Ffowcs Williams–Hawkings equation solver that uses Farassat's formulation 1A for tonal noise prediction. Broadband noise, specifically airfoil self-noise, is predicted using the semiempirical Brooks, Pope, and Marcolini (BPM) model. PSU-WOPWOP uses the time-dependent data (e.g., geometry, motion, sectional airloads, and angle of attack) generated from CHARM as inputs to compute the noise at any number of observers on the ground or moving with the aircraft.

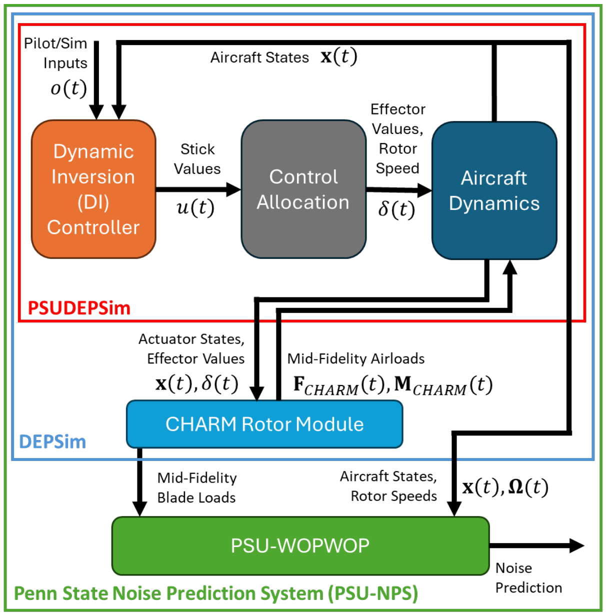


Figure 1. Overview of the different components of the PSU-NPS. CHARM: Comprehensive Hierarchical Aeromechanics Rotorcraft Model, DEPSim: Distributed Electric Propulsion Simulator.

Figure 2 represents the layout of the large reconfigurable UAS developed by Penn State in a X8 configuration. The rotor diameter is 0.71 m, and the vehicle weight is 159 N. The front of the vehicle is aligned with the x-axis. For the current study, the X8 flies in an “X” configuration, with two rotors toward the front of the vehicle.

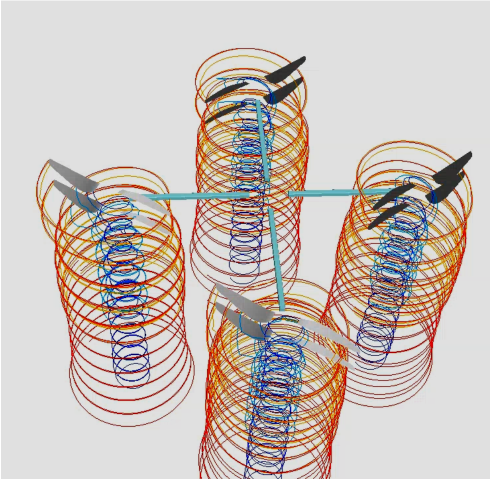
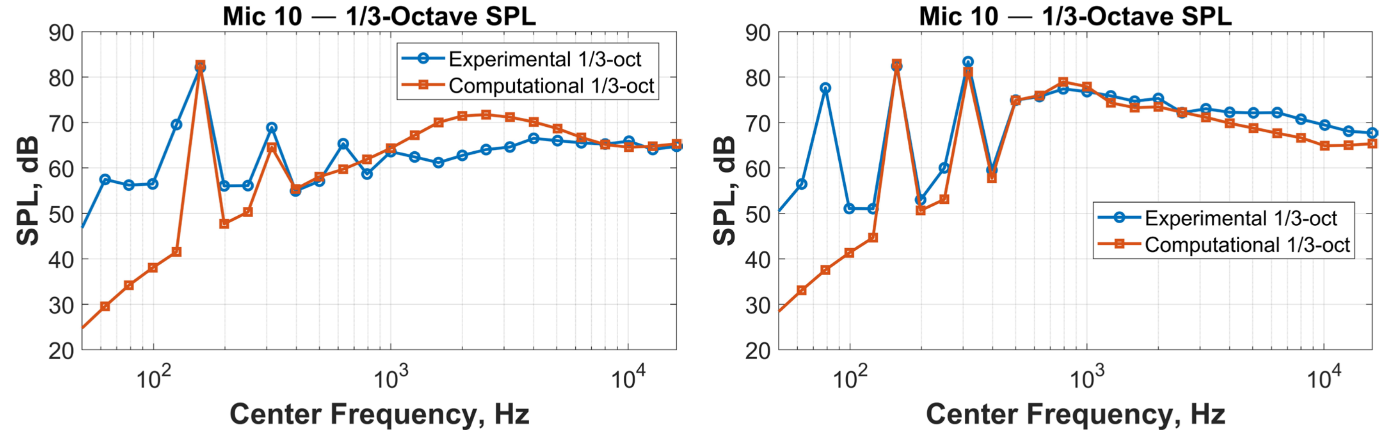


Figure 2. Computational model of X8 with wake during hover.

To validate the results of X8 using the Penn State NPS, a frequency-domain comparison was performed for the two stacked rotors operating in co- and counter-rotating configurations. The predicted acoustic spectra in hover were compared against previously acquired data for a 0.46 m diameter rotor operating at 4,600 rotations per minute (RPM) with combined thrust of 48 N. Figure 3 compares the 1/3-octave spectra for co- and counter-rotating stacked rotors separated with a vertical distance between the rotors of 20% of one rotor radius. A phase control system was used during the experiment to maintain a rotor-to-rotor phase offset of $\psi_r = 0^\circ$. For the co-rotating configuration, this results in the upper and lower rotor blades being stacked directly over one another. For the counter-rotating configuration, the blades cross over one another at the same position every revolution. Measurements were obtained from a microphone positioned at a distance (d) of 2 m from the rotors and an elevation angle (ϕ) of -28° below the rotor plane.

Figure 3a presents the measured and predicted spectra for the co-rotating configuration. The model predicts the lower-frequency (mostly tonal) contribution levels reasonably well but overpredicts the noise levels between 1 kHz and 5 kHz. Figure 3b presents the spectra for the counter-rotating configuration. Here, the lower-frequency contribution agrees well with the experiment, but the model underpredicts the higher-frequency components, particularly from 5 to 10 kHz. Note that in both cases, a shaft order (1/rev) tone is present in the measured data due to test stand vibrations and imbalances between the rotor blades; these effects are not modeled in the simulations.

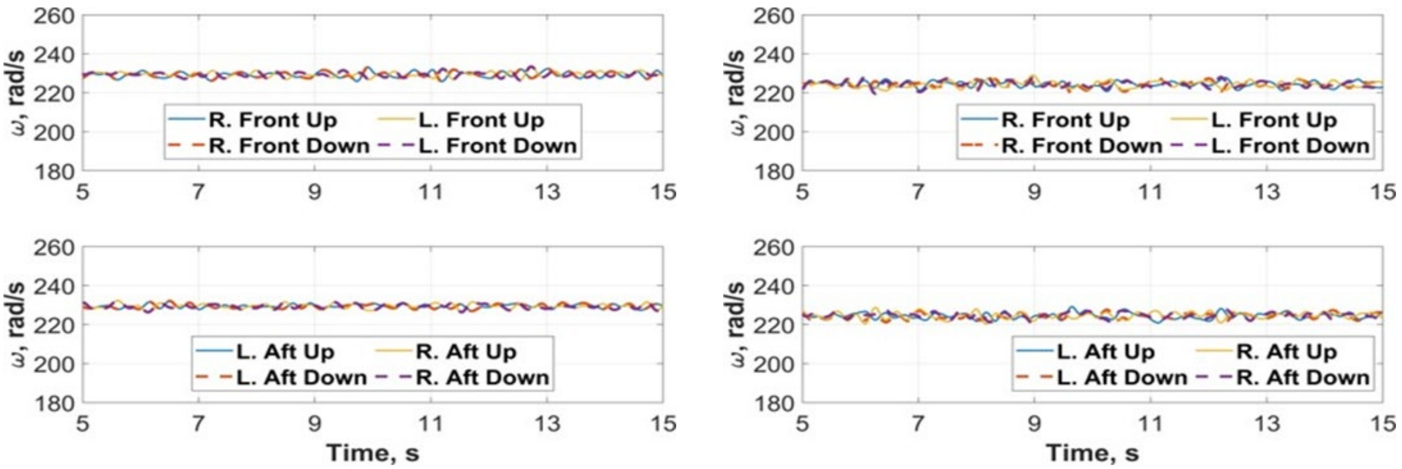


(a) Co-rotating

(b) Counter-rotating

Figure 3. 1/3-octave spectra comparison of stacked rotors, (a) co-rotating and (b) counter-rotating, with zero phase offset, separated by 0.2R, with the microphone positioned at $d = 80$ in and $\phi = -28^\circ$ (below the rotor plane)

The X8 vehicle was trimmed to produce 155 N thrust to hover in both the co-rotating and counter-rotating configurations. The phase offset between rotors is again held at zero. Figure 4 shows that the co-rotating rotors operate at a slightly higher RPM, but in both configurations the eight rotors maintain closely grouped RPMs, indicating consistent thrust distribution during hover.



(a) Co-rotating **(b) Counter-rotating**

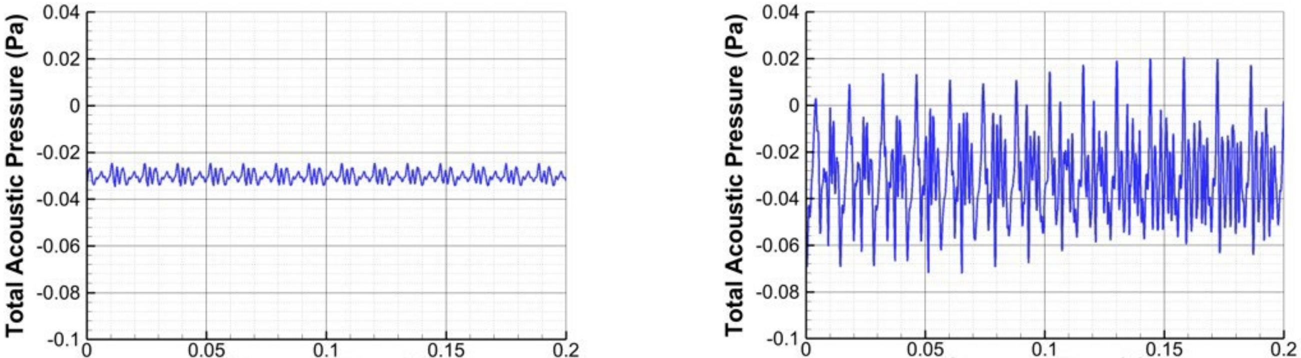
Figure 4. Comparison of rotor revolutions per minute (RPM) during hover for an X8 configuration with (a) co-rotating and (b) counter-rotating rotors.

Figure 5a shows the vertical-force variation with azimuth $\left(\frac{dF_z}{d\psi}\right)$ for the co-rotating configuration in hover, where the small fluctuations indicate weak rotor–rotor interaction. Figure 5b, in contrast, shows the counter-rotating case, where the loading variations are larger and more irregular, demonstrating stronger wake-induced interaction across the rotor disk.

(a) X8 Co-rotating **(b) X8 Counter-rotating**

Figure 5. Variations in vertical force with respect to azimuth $\left(\frac{dF_z}{d\psi}\right)$ during hover in rotor disk, (a) X8 co-rotating and (b) X8 counter-rotating.

Figure 6 shows the tonal acoustic pressure time histories for the co-rotating and counter-rotating configurations. The counter-rotating configuration exhibits strong impulsive interaction noise, arising from intensified rotor-rotor interactions. In contrast, the co-rotating configuration shows smoother and lower-amplitude pressure fluctuations, indicating weaker aerodynamic interactions and reduced impulsive content.



(a) Co-rotating **(b) Counter-rotating**

Figure 6. Acoustic pressure time-history comparison of (a) X8 co-rotating and (b) counter-rotating configurations for an observer positioned at d = 20R in and $\phi = -80°$ (below the rotor plane).

Publications

Chaudhary, R., Valente, V., Mukherjee, B., Jue, A., Brentner, K., S., & Greenwood, E. (2024, May 7-9). *Understanding Takeoff and Landing Noise for Small Multirotor Vehicles* [Conference paper]. Vertical Flight Society's 80th Annual Forum & Technology Display, Montreal, Canada. https://doi.org/10.4050/F-0080-2024-1157

Outreach Efforts

The investigation team holds monthly meetings with FAA and an external advisory board consisting of a dozen interested parties from government and industry.

Awards

None.

Student Involvement

PhD student Rupak Chaudhary is the primary person responsible for conducting UAS noise predictions by using the Penn State NPS (DEPSim/CHARM/PSU-WOPWOP). These predictions include the flight dynamics of the vehicle based on the DEPSim multirotor flight simulation code, including the variation in rotor RPM required to perform the maneuver. The resulting acoustic predictions are compared with experimental data from both outdoor acoustic flight test measurements and laboratory experiments conducted under controlled conditions.

Plans for Next Period

- Conduct simulations for different maneuvers that are representative of multirotor aircraft operations to comprehensively study the generated noise and inform the development of UAS noise measurement techniques.
- Examine additional cases with varied rotor phase offsets to assess how configuration changes influence the vehicle's radiated noise.

Task 2 – Microphone Array Design Using Computational Modeling

The Pennsylvania State University

Objective

To design a microphone array, informed by computational modeling, to capture near-instantaneous noise radiation from multirotor UAS/UAM vehicles. The flight state of these vehicles changes over time, which makes it difficult to characterize the directionality of the noise using conventional measurement approaches. The proposed "snapshot" array is intended to resolve these time-varying noise characteristics by measuring noise across a wide range of emission angles over a short time interval.

Research Approach

The Penn State NPS was used to evaluate and design microphone array layouts. The selected maneuver was first simulated with a high-density observer grid to generate a detailed acoustic noise hemisphere. The number of observers was then reduced to match the available microphone count, and their positions were optimized to reproduce the same hemispherical noise features with a sparse array. Finally, the selected microphone locations on the hemisphere were projected onto the ground to establish the physical snapshot array geometry.

Milestones

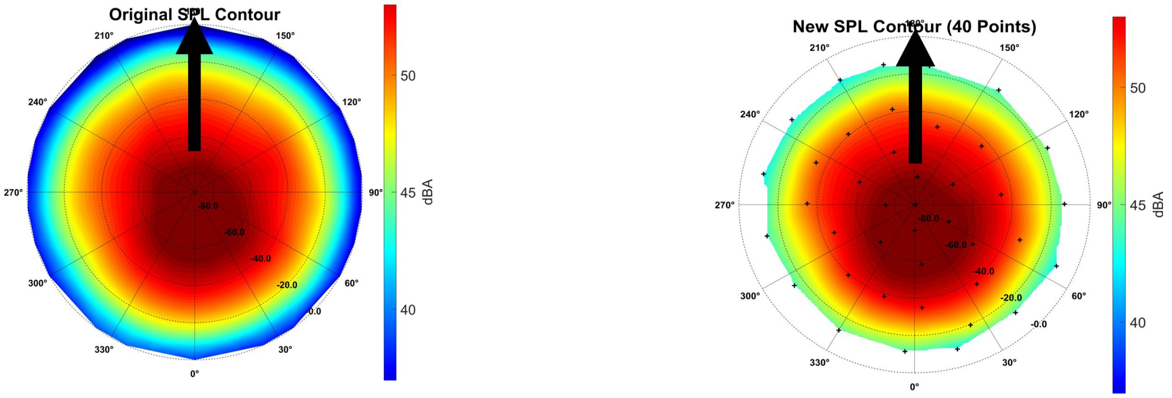
- Generate high-resolution noise hemispheres using NPS.
- Design and optimize a snapshot microphone array.
- Project microphone array to the ground and validate the layout.

Major Accomplishments

Noise hemispheres are traditionally generated using a linear microphone array placed perpendicular to the vehicle flight path. As the aircraft flies over the line of microphones, acoustic data are captured at multiple azimuth and elevation angles, allowing a hemispherical noise map to be reconstructed. This approach works well when the vehicle behaves as a steady-state acoustic source, e.g., for a conventional aircraft flying at constant speed and attitude. However, this assumption breaks down for UAS and UAM vehicles, whose attitudes, thrust levels, and operating states change rapidly—especially during transient maneuvers such as climbs, descents, and accelerations. These time-varying states produce corresponding changes in the emitted noise, making a steady-state linear array reconstruction less accurate.

To address this limitation, a snapshot array methodology is employed. A snapshot array captures acoustic data simultaneously from many angles over a short time window, effectively “freezing” the vehicle at a specific moment. By treating the vehicle as a stationary source only for the duration of this short window, the snapshot approach provides a near-instantaneous noise hemisphere suitable for analyzing transient or maneuvering flight conditions.

A descent maneuver with a flight-path angle of $\gamma = -15^\circ$ and a vehicle speed of 10 mph was simulated in PSU-NPS using the PSU reconfigurable hexacopter model. The original noise hemisphere for this maneuver was generated using a high-resolution grid of 933 observer locations (Figure 7a). To match the density of the experimental microphone layout, a second noise hemisphere was reconstructed using only 40 observer positions using k-mean clustering method to represent a number of microphones that could practically be deployed in the field. Cubic interpolation was applied to these 40 points to produce a continuous sound pressure level (SPL) contour (Figure 7b). As shown in Figure 7, the reduced-observer contour retains the primary directivity characteristics of the original high-resolution hemisphere.



(a) Full resolution

(b) Reduced observers

Figure 7. Stereographic projection of lower noise hemisphere of radius 50R during descent maneuver $\gamma=-15^\circ$ and vehicle speed of 10 mph, at (a) full resolution and with (b) reduced observers.

To experimentally support snapshot-array noise reconstruction, a ground array of 23 microphones was deployed (Figure 8). Twenty microphones were arranged to cover half of a hemispherical surface, providing angular resolution across a wider elevation angle. Three additional microphones were placed to evaluate left-right symmetry. A separate seven-microphone linear array was also deployed to capture propagation characteristics along the flyover direction which will be used to study difference. All acoustic flyovers are planned to be conducted at a nominal altitude of 50 ft above the center of the array.

(a) Plan view **(b) Google Earth view of actual field deployment**

Figure 8. Snapshot microphone array, (a) plan view and (b) Google Earth® view of actual field deployement.

Publications

None.

Outreach Efforts

The investigation team holds monthly meetings with FAA and an external advisory board consisting of a dozen interested parties from government and industry.

Awards

None.

Student Involvement

PhD student Rupak Chaudhary is the primary person responsible for designing the snapshot microphone array. Dr. Vítor T. Valente provided guidance and mentorship throughout the development of the snapshot microphone array.

Plans for Next Period

- Conduct acoustic flight tests for both steady maneuvers—such as hover and level flight—and transient maneuvers, including climb, descent, and turning flight,
- Use the snapshot microphone array to capture near-instantaneous acoustic hemispheres during these operating conditions.

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Task 3 – Development and Testing of a Reconfigurable Multirotor UAS

The Pennsylvania State University

Objectives

The objectives of this task are (a) to design and develop a multirotor UAS research vehicle that can be easily reconfigured, and (b) to study the acoustic effects of different UAS vehicle configurations and their influence on the noise measurement and data processing approaches developed in this project.

Research Approach

Small and large reconfigurable multirotor UAS aircraft architectures were developed in previous years of the project, with the smaller vehicle serving as a testbed for design concepts that were later integrated into the larger, more capable aircraft. Ground tests and several flight tests of the UAS were conducted prior to acoustic data collection to support the development of the aircraft systems. One focus of these tests was validated upgrades intended to improve the reliability of the telemetry and on-board data recording systems of the aircraft systems prior to acoustic data collection flights. Onboard instrumentation includes a real-time kinematic Differential Global Positioning System (DGPS), an inertial measurement unit, individual rotor RPM and phase measurements, and an air-data system including measurements of outside air temperature, static pressure, humidity, and ultrasonic measurements of true airspeed. Two large multirotor are available, one in a hexacopter configuration and another in an X8 configuration (quad with coaxial set up).

Milestones

- Identify acoustically significant configuration changes to be made on the vehicle.
- Complete initial design of the vehicle and selection of sensors.
- Design control system.
- Perform ground and flight testing.

Major Accomplishments

Two major tasks were performed within the current period: (a) weight optimization and (b) improvements in the onboard recording of the states.

Weight Optimization

As additional sensors were installed on the vehicles, vehicle’s endurance per battery charging cycle decreased, which limited the number of flights that could be completed in a single day. To address this issue, a weight-reduction effort was carried out on both platforms, focusing mainly on structural components and supports for the sensor suite. After this work, the Hexa reached a final system weight of 30.9 lb, and the X8 reached 32.4 lb, reflecting the gains from simplifying structures and reducing unnecessary mass. Each vehicle includes the required radio control (RC) system, with Global Positioning System (GPS) added as needed, for a combined weight of 0.8 lb. Depending on the mission, the Li560 and Wx150 sensors may also be installed, adding 4.7 lb (when both used). These updates help balance structural weight, control hardware, and sensor payloads so that the vehicles can achieve better endurance and more efficient operations.

Onboard Recording of States

A new sensor-recording system has been introduced to capture detailed information from each motor or rotor during flight. Main parameters being logged include raw RPM, raw rotor azimuth angle, motor current and voltage, and input percentage command. This implementation relies on updated motor firmware that communicates through the Controller Area Network (CAN) bus, allowing the system to decode two dedicated messages for logging. Data acquisition is handled by a Raspberry Pi 4 equipped with a CAN bus hat and running custom C++ software. Parameters such as the number of motors, their rotation direction, and the desired read or save rates can be adjusted through an external configuration file, eliminating the need to recompile the code. A complementary Python® tool supports quick verification in the field. Each motor transmits data at 100 Hz (configurable in the firmware), although overall throughput is constrained by baudrate limits, allowing approximately 173 Hz total on the Hexa and 130 Hz on the X8. The system writes data to file at 1 Hz and remains agnostic to vehicle layout, currently supporting up to twenty motors.

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Publications
None.

Outreach Efforts
The investigation team holds monthly meetings with FAA and an external advisory board consisting of a dozen interested parties from government and industry. Technical data regarding the reconfigurable multirotor UAS have been shared with investigators from the National Research Council Canada, the Georgia Institute of Technology, the University of Salford, Texas A&M University, and the NASA Langley Research Center. Discussions are ongoing regarding potential opportunities for collaboration.

Awards
None.

Student Involvement
Dr. Vítor T. Valente is primarily responsible for the design, assembly, and configuration of the UAS.

Plans for Next Period
- Maintain all these systems.
- Make improvements where necessary to add additional sensors.

Task 4 – UAS Noise Measurement and Analysis
The Pennsylvania State University

Objective
The objective of this task is to conduct an acoustic flight test campaign to collect noise data for a variety of UAS vehicles under a variety of operating conditions and configurations.

Research Approach
Acoustic measurements of a flying UAS were conducted at the Mid-State Regional Airport (KPSB), surrounded by the Moshannon State Forest and Black Moshannon State Park near Philipsburg, Pennsylvania. Noise measurements were made for the large reconfigurable research UAS described in the previous tasks. The vehicle was flown through a range of operating conditions, including hover, forward flight at several speeds, climb and descent, yaw and maneuvers for calibration of the weather system onboard. For all maneuvers, the aircraft was flown at different altitudes, from near ground level up to 400 ft above ground level, to evaluate the ability to scale UAS noise levels measured at one flight altitude to another. Acoustic measurements were made with Penn State's networked, battery-powered, and field-deployable acoustic data acquisition system capable of sampling at a frequency up to 125 kHz at 24-bit resolution with subsample accurate (within 200 ns) GPS time synchronization across all nodes. A microphone array was designed to capture both spatial and temporal variations in the radiated noise. Weather instrumentation was also deployed, including measurements of wind speed, direction, temperature, pressure, and humidity, both on the vehicle and at ground level near the ground control station. The weather station used at ground level is the same make and model of the one mounted on the vehicle.

Milestones
- Collect a baseline acoustic, performance, and meteorological dataset of UAS noise measurements
- Analyze the data to quantify and understand the variability in UAS noise.

Major Accomplishments
The major accomplishments were performed during this evaluation period.

Flight Testing
Due to varies reasons beyond the control of the team, relatively few flight tests were conducted in 2025. The ones that happen were mostly related to the air-data system calibration already described in previous reports. The team expects to resume flight testing in new campaigns as the weather allows.

Data Analysis

In a different effort, the data analysis process was uniformized in terms of creating the packet structure to facilitate post-processing analysis. The software used was Matlab.® The current supported flight conditions are:

- H - Hover
- HW - Hover with added weight
- AD - Ascent/Descent
- FF - Forward flight
- FFW - Forward flight with added weight
- WCAL - Weather station calibration
- XFLY - X or + pattern for weather data collection
- YAW - Yaw maneuver on top of a specific microphone

Each condition filename (or flight) is accompanied by "_XXX.mat" where XXX is a number. For example, H_134.mat represents the data from a hover test with number 134. The specifics of this flight (e.g., date, time of the day, altitude set points, etc.) will be in a test matrix from the day when the flight happened and should be provided separated from the .mat itself.

The structure includes onboard flight data from the flight controller (PX4), data from the weather station at ground level (WX150), data from weather station onboard (WX150 and LI560), onboard recording of the states of the motors (custom) and general information about the test. Each variable (onboard log or microphone recording) has their own time vector since the sampling frequency is not always the same among different sources. However, all data are synchronized to the same Coordinated Universal Time (UTC) time reference.

A function was created to process a .mat file pointed by the user generating a set of default plots. It uses user inputs to select a file and from there multiple plots are generated. They include:

- Latitude x Longitude of a flight in a geomap with microphone locations
- North x East x Altitude of a flight in a three-dimensional (3D) plot with microphone locations
- Attitude timeseries
- Altitude timeseries
- Velocity timeseries
- Pressure time series of selected microphones
- SPL time series of selected microphones

User may select more than one microphone to be plotted. By using the file structure above, the user can implement their own functions for a more in-depth/specific results.

A different script was also created to allow for splitting an original file into many by visually selecting points of interest. The result of this second script is a set of segments, using the same file structure, separated by the points the user selected. This allows for the selection of specific sections of each flight.

Publications

None.

Outreach Efforts

The investigation team holds monthly meetings with FAA and an external advisory board consisting of a dozen interested parties from government and industry. Data collected for UAS under this task may also be provided to collaborators at the University of Salford and the NASA Langley Research Center to enable psychoacoustic evaluations of UAS noise by using their auralization and human participant testing capabilities.

Awards

None.

® Matlab is a registered trademark of The MathWorks, Inc., Natick, Massachusetts.

Student Involvement

Dr. Vítor T. Valente, PhD students Joel Rachaprolu and Rupak Chaudhary, conducted acoustic flight testing of the large reconfigurable UAS and participated in analysis of the measured data.

Plans for Next Period

Resume and expand flight testing campaigns to evaluate different vehicle configurations as well as microphone array configurations.

Task 5 – Development of a Source Separation Process for Distributed Propulsion Vehicles

The Pennsylvania State University

Objective

The objective of this task is to develop a process for separating the noise generated by rotors or propellers at non-constant, but potentially similar, RPM values from flyover measurements of UAS and UAM vehicles. By separating noise generated from each rotor, it will be possible to develop a more repeatable characterization of the noise of the entire aircraft.

Research Approach

The SSP was developed in this task is a two-step process that combines a time-domain de-Dopplerization procedure and Vold–Kalman order tracking filter. This approach will de-Dopplerize the acoustic measurements and separate the individual rotor noise components, with the capability to extract time-varying impulsive noise. Performing this source separation in the specified time domain will enable the application of a wide range of post-processing techniques in both the time and frequency domains. Each step of the SSP was verified on computational and experimental/flight test data to assess the performance. Acoustic analysis with the SSP components was also performed, in which individual steps of the SSP were isolated and applied to different datasets. This process was applied to the Bell® 430 helicopter and was extended to separate the tonal noise generated by individual rotors of the large reconfigurable UAS in the previous reporting period. During this period, the approach was additionally applied to simulated data to allow the accuracy of the approach in separating the individual rotor noise components to be quantified.

The flowchart in Figure 9 outlines the steps of the approach used to quantify the accuracy of the SSP. First, a computational setup is used to predict the noise generated by the hexacopter modelled in simulation using the framework described in Task 1 based on the aircraft developed and then built in Task 3.

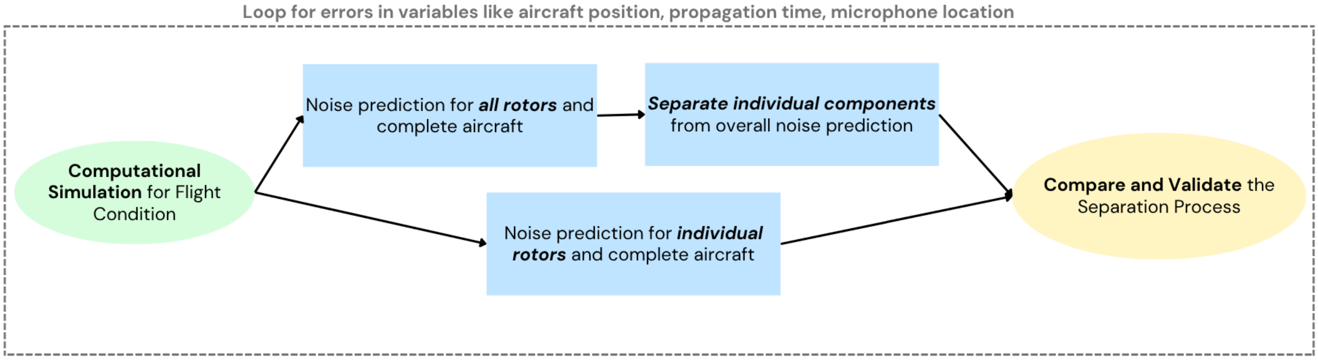

Figure 9. Outline of the approach used to quantify the accuracy of source separation process (SSP).

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First, noise is predicted for entire aircraft with all six rotors using the computational setup and then separated into individual components using the SSP. Second, noise is predicted for each rotor individually with the same computational setup as the previous predictions. Then, the separated noise components are compared to the "true" predicted components to reveal the accuracy of the separation. This approach and results for a test hover test case are presented in the accomplishments section.

Milestones

- Develop an SSP for stationary acoustic measurements.
- Implement a de-Dopplerization approach to convert non-stationary measurements to a stationary frame.
- Apply the process to simulated and measured data to evaluate the effectiveness of the separation.
- Apply the process to multirotor aircraft acoustic measurements to extract acoustic components for each rotor.
- Study the accuracy of the SSP to separate individual rotor components.

Major Accomplishments

The results of SSP on hover are provided in this section. The approach was applied to forward flight, with similar results. Figure 10 shows the rotor speed histories during hover. The six rotors maintain nearly constant speeds, with only minor fluctuations induced by the flight control system as it stabilizes the vehicle against small disturbances. In this case, data from a microphone under the aircraft are used for the analysis.

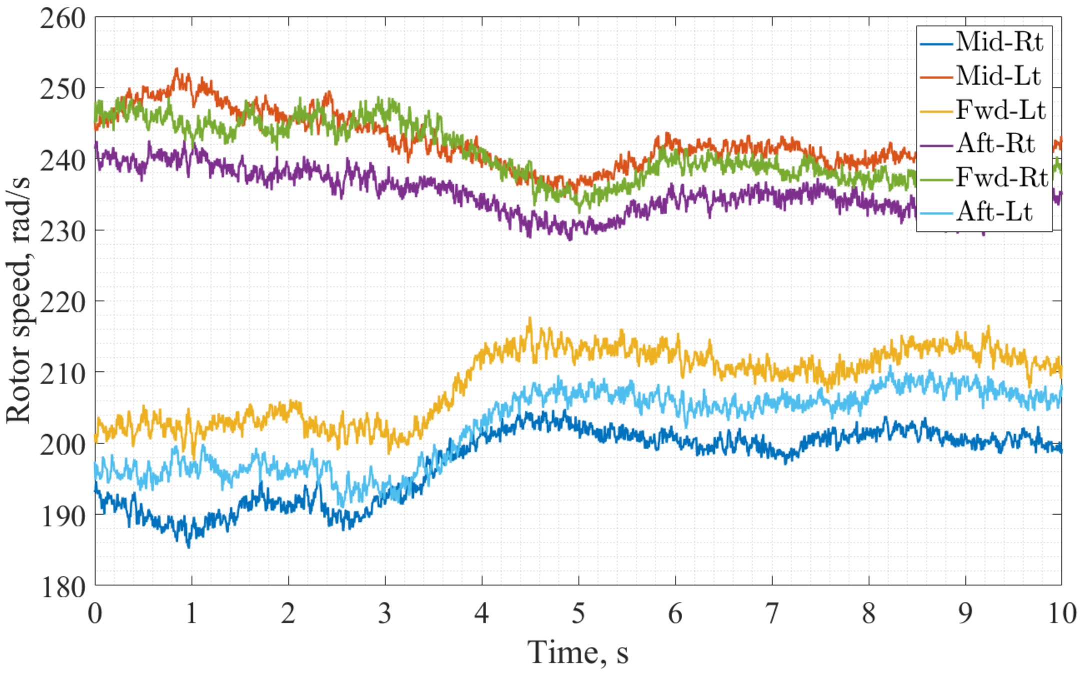

Figure 10. Rotor rotations per minute (RPM) time history in hover case.

Using the aircraft with the rotor speeds shown in Figure 10, the separation was performed on the noise prediction (see Figure 11). The separation was performed for the first 15 harmonics of the rotor blade passing frequencies. During this period, the aircraft was fairly stable, and we can see that each of the rotor has a distinct pulse shape with respect to each other. This reveals distinct noise features of each of the rotors.

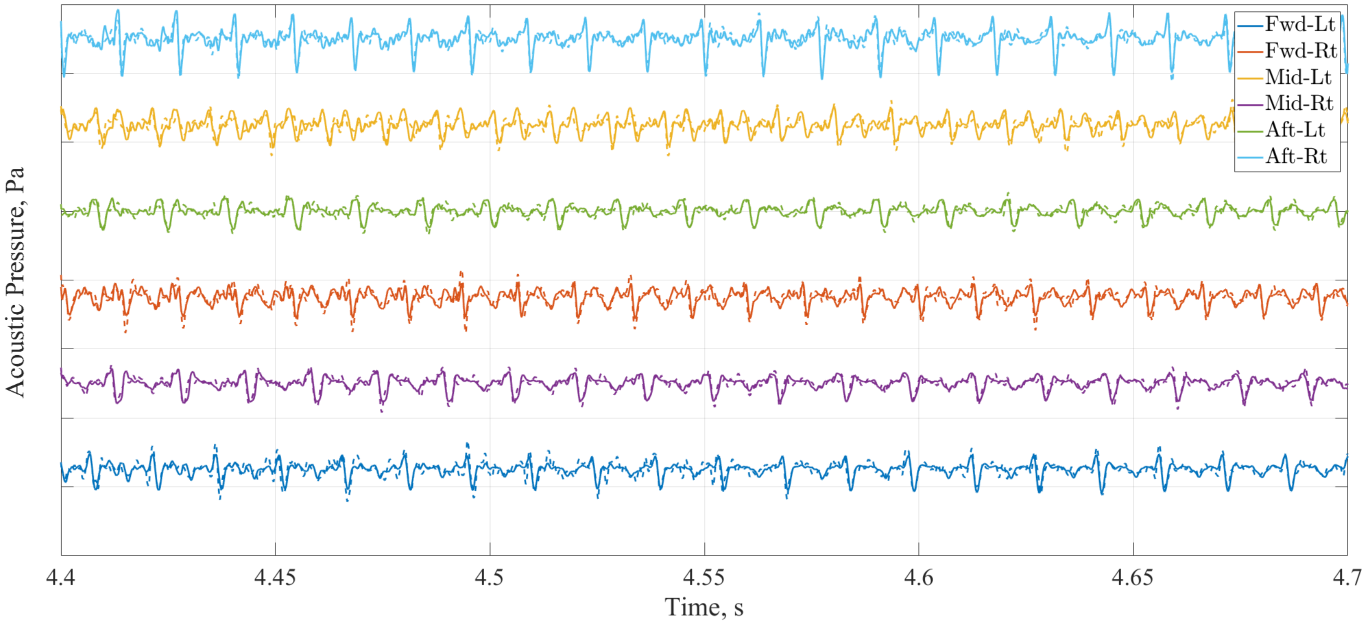

Figure 11. Separated components of all the six individual rotors using the source separation process (SSP) for the hexacopter data.

In addition to that, in Figure 11, the solid line is the separated component, and the dotted line is the predicted component for each rotor. During the time period shown, the separated component is quite close to the predicted component reassuring the separation is accurate. To take a closer look, if we plot a shorter time period in the same formation as a traditional placement of rotors in a hexacopter, the distinction would be much clearer.

Figure 12 is the separated acoustic pressure time series pulse shaped for each individual signal arranged according to rotor placement in a hexacopter. The distinctions between each of the rotors are clear, as well as the agreement with the predicted acoustic pressures. It is clear that the separation is accurate in the time domain, following this, a frequency domain plot for the same time period is shown in Figure 12.

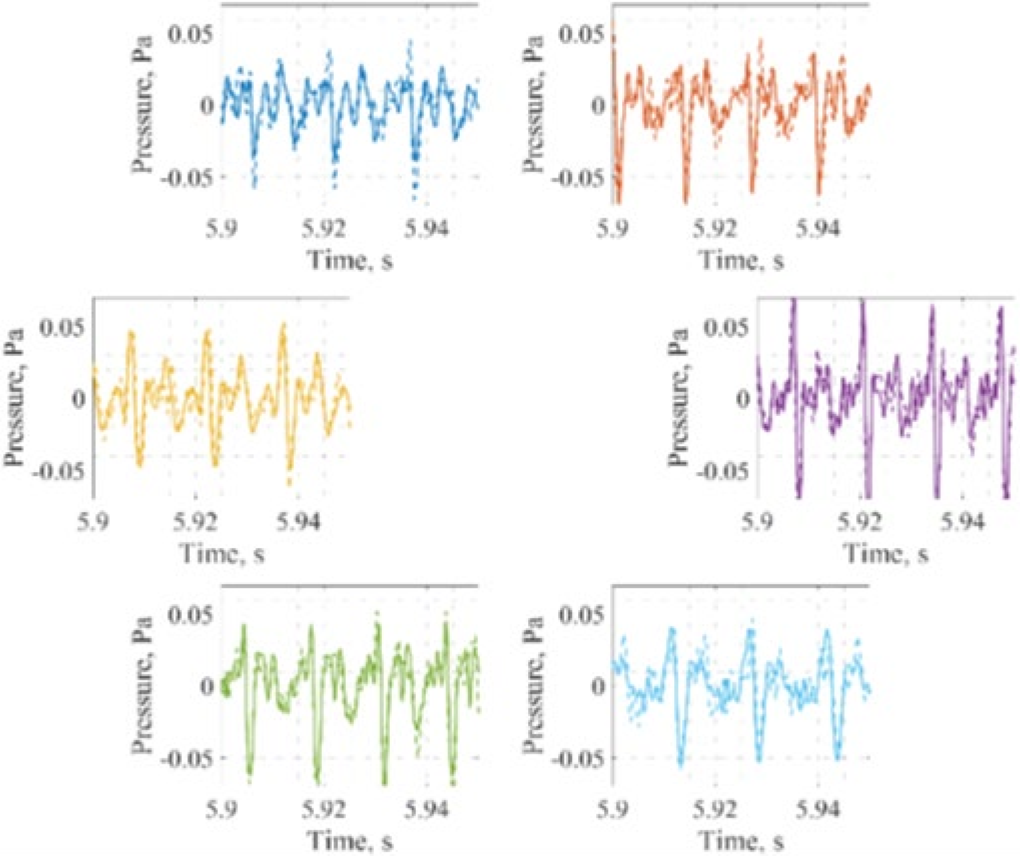

Figure 12. Separated acoustic pressure time series signals for each rotor on the aircraft over a short time window arranged in a hex-format.

The spectra shown in Figure 13 is for the same time period as the acoustic pressure time series as the signals shown in Figure 12. In the frequency domain, looking at the tonal content of the separated and the predicted signals, it is evident that the SSP can accurately separate the individual rotor tonal noise contributions.

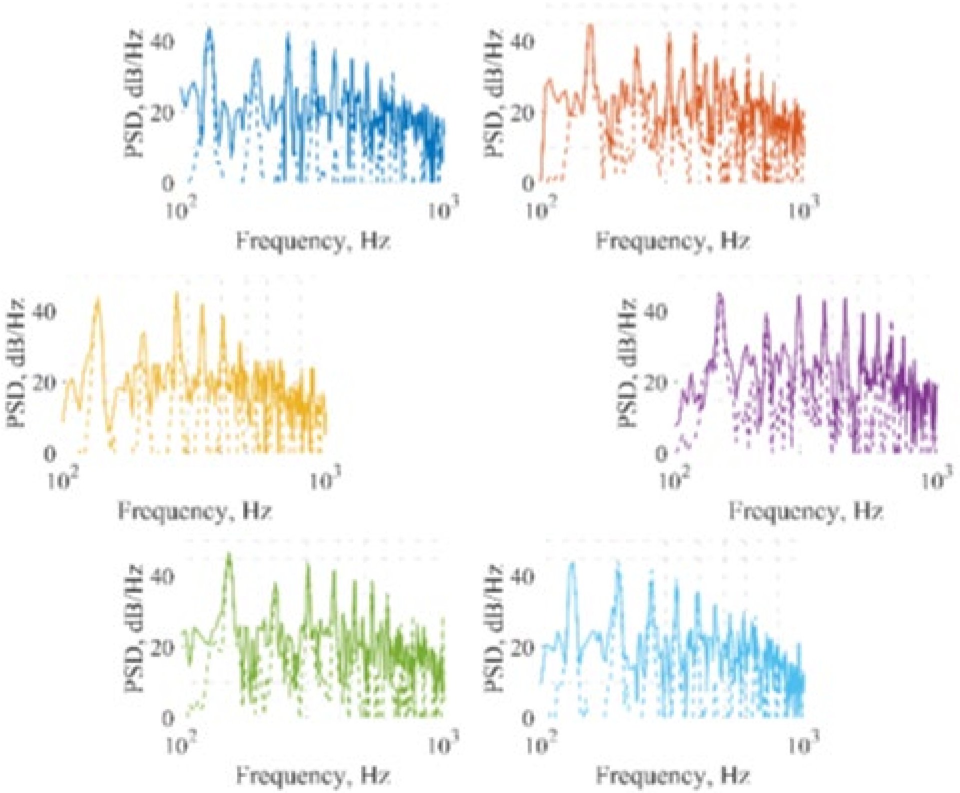

Figure 13. Separated spectra for each rotor for the same time period as the time series signals arranged in a hex-format.

Publications

Rachaprolu, J., & Greenwood, E. (2024). Helicopter Noise Source Separation using an Order Tracking Filter. *Journal of the American Helicopter Society*. https://doi.org/10.4050/JAHS.69.012006

Rachaprolu, J., Valente, V. T., ElSharkawy, E., & Greenwood, E. (2024, May). *Multirotor Noise Source Separation and Characterization from Ground-Based Acoustic Measurements* [Conference presentation]. Vertical Flight Society Forum 80, Montreal, Canada.

Outreach Efforts

The investigation team holds monthly meetings with FAA and an external advisory board consisting of a dozen interested parties from government and industry. The SSP developed under this task has been provided to Blue Ridge Research and Consulting, which has applied the method to isolate noise generated by an Urban Air Mobility vehicle.

Awards

Joel Rachaprolu was awarded the Vertical Flight Foundation Scholarship award.

Student Involvement

PhD Student Joel Rachaprolu developed and tested the SSP with experimental measurements of helicopter and multirotor data, and has now been extended to demonstrate the accuracy with hexacopter data.

Plans for Next Period

All major milestones for the task have been completed. However, in the next period, the SSP will be applied to a wider range of conditions to validate its accuracy. Improvements will be made, as necessary, to increase the robustness of the process for future use on multirotor vehicles.

Task 6 – Noise Reduction through Synchrophasing

The Pennsylvania State University

Objective

The objective of this task is to develop and experimentally validate an active noise reduction approach for multirotor aircraft based on phase synchronization of the rotors.

Research Approach

A fully electronic rotor phase control scheme was developed for a hexacopter small UAS (sUAS) designed and built at Penn State. The process begins by characterizing the acoustics of each rotor of the vehicle by using an acoustic array installed in Penn State's flow-through anechoic chamber. These acoustic signals were processed to allow the results to be generalized to any other far-field observer location. An optimization approach was then applied to identify the rotor phase combinations that reduce the noise of the vehicle at one or more observer locations. An electronic phase controller was then used to maintain the target phase relationships between the rotors, and the radiated noise of the entire vehicle was measured and assessed.

Milestones

- Adapt an electronic phase control method to a fixed wing UAS.
- Validate electronic phase control method in free flight.

Major Accomplishments

An off-the-shelf fixed wing airplane was acquired and modified to allow the installation of multiple motors on the wing. The phase control method, previously used in a multirotor electric vertical take-off and landing (eVTOL), was modified to account for the differences in the geometry of the vehicle being used.

Experimental approach

This section presents the approach followed to develop and demonstrate a synchrophasing strategy on a fixed wing distributed electric propulsion (DEP) aircraft configuration. The noise control method is based on previous work and is intended to control the directionality of the radiated noise by modifying the relative propeller phases, thereby influencing the tonal components of the acoustic field. Synchrophasing methodology includes three main steps: acoustic characterization of the propellers, optimization for the set of phases achieving the desired noise control target, and implementation of phase controller itself.

For this work, the first step was performed using the CHARM in combination with PSU-WOPWOP. CHARM provides a mid-fidelity framework for predicting the aerodynamics of rotor- and propeller-driven aircraft, employing a panel-based method for the representation of airframe aerodynamics. PSU-WOPWOP is a general-purpose aeroacoustics solver, implementing Farassat's Formulation 1A of the Ffowcs Williams–Hawkings equation. Time-resolved data generated by CHARM Standalone serve as inputs to PSU-WOPWOP for the computation of the associated acoustic fields.

For each propeller on the aircraft, the average acoustic pressure over one propeller revolution was generated using CHARM and PSU-WOPWOP, considering the expected operating conditions of the propeller. Assuming linear superposition of the propeller waveforms, an optimization is conducted to minimize the average mean square pressure across a subset of observers by adjusting the set of relative phases. By minimizing the sum of the mean-squared pressures, the average SPL is also reduced in that region. Conversely, the sum of the mean-squared pressures can be maximized to determine the phase combinations that will increase the SPL in the target region. The phase controller constitutes the final stage of the noise attenuation strategy. Its function is to regulate the relative phase of each rotor with respect to a virtual reference, which depends on the rotor's instantaneous phase, the target phase offset, and its rotational speed.

Vehicle Configuration

The vehicle to be used in this work is a modified Pilatus® PC6 remote-controlled aircraft. The basic specifications of the original aircraft are presented in Table 1 below.

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Table 1. Original aircraft characteristics.

Characteristic	Value
Model Scale	1/6
Wingspan	107.0 in.
Length	78.7 in.
Empty Weight	310.4 oz
Material	Balsa and Plywood

In its original form, the vehicle is designed for a single 20-in. by 8-in. propeller attached on the nose. Modifications were made to both wings and fuselage to include a distributed electric propulsion system with eight Vertiq® 4006 770 kV motors with APC® 10-in. by 10-in. propellers in both clockwise (CW) and counterclockwise (CCW) rotation configurations. The avionics include an onboard computer, an inertial measurement unit, and a GPS unit. A picture of the current status of the vehicle is shown in Figure 14 with dimensions given from the centerline of the fuselage.

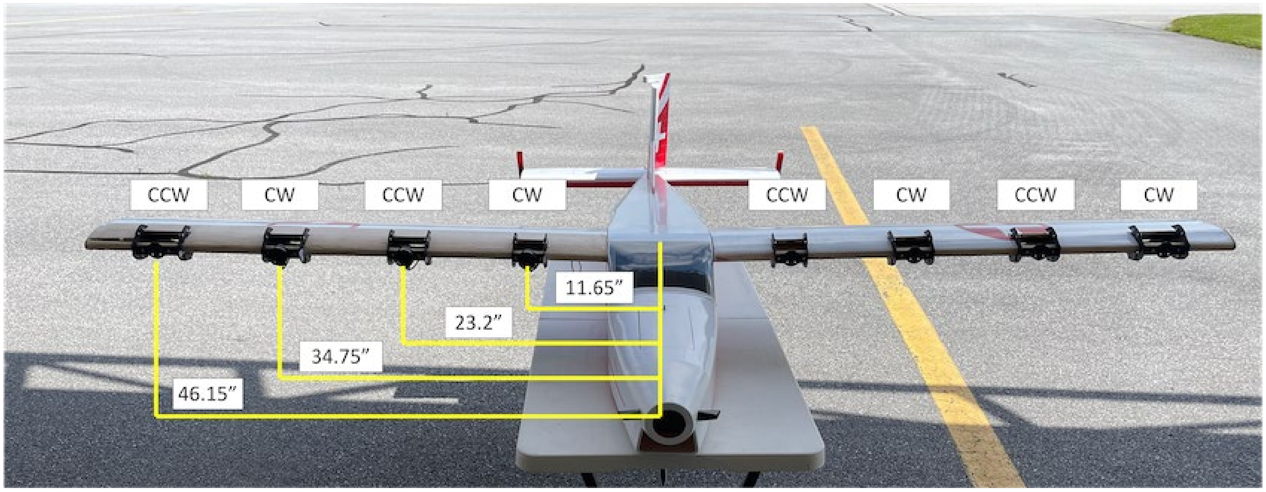

Figure 14. Modified Pilatus PC-6 model with a synchrophasing distributed electric propulsion (DEP) system. The direction of rotation of the propellers is indicated as in the picture.

Simulations were performed comparing performance data available for the selected propeller versus the original propeller suggested for the unmodified vehicle design. Figure 15 below presents the result of these simulations, showing that for an expected range of model velocity around 60 mph, the combination of eight smaller propellers will provide higher power and thrust in comparison to the original propeller. The difference of 20%-30% also accounts for performance losses given the change from one propeller to eight propellers set up. The target set point for the group of motors for angular velocity is 9,000 RPM, which corresponds to slightly less than 50% of the motor capabilities. The original motor set point for the comparison was at 7,000 RPM, which corresponds to approximately 60% of the suggested motor for the model without modifications.

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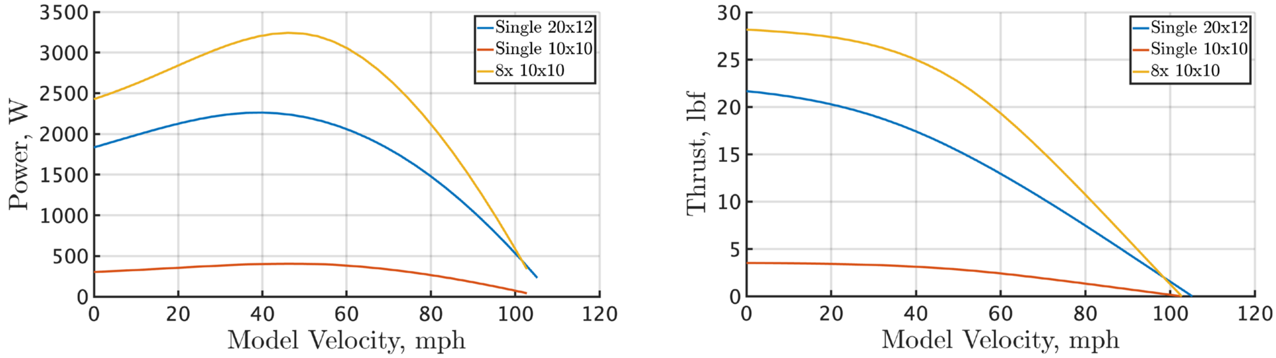


(a) **(b)**

Figure 15. Simulation comparing the originally suggested blade with the newly selected blade, model velocity versus (a) power and (b) thrust.

Microphone Array Configuration

The proposed location is shown in Figure 16 The center microphone (Mic 6) is directly underneath the vehicle path (blue line). On each side, five microphones are spaced at successively increasing 9° increments of elevation angle, considering the target flying altitude of 100 ft. The last microphone on each side (Mic 11 and Mic 1) is placed at 100 ft from the centerline of the array, providing similar sideline angles for later analysis. This microphone array provides a ±45° sideline angle measurement region under the target flight path.

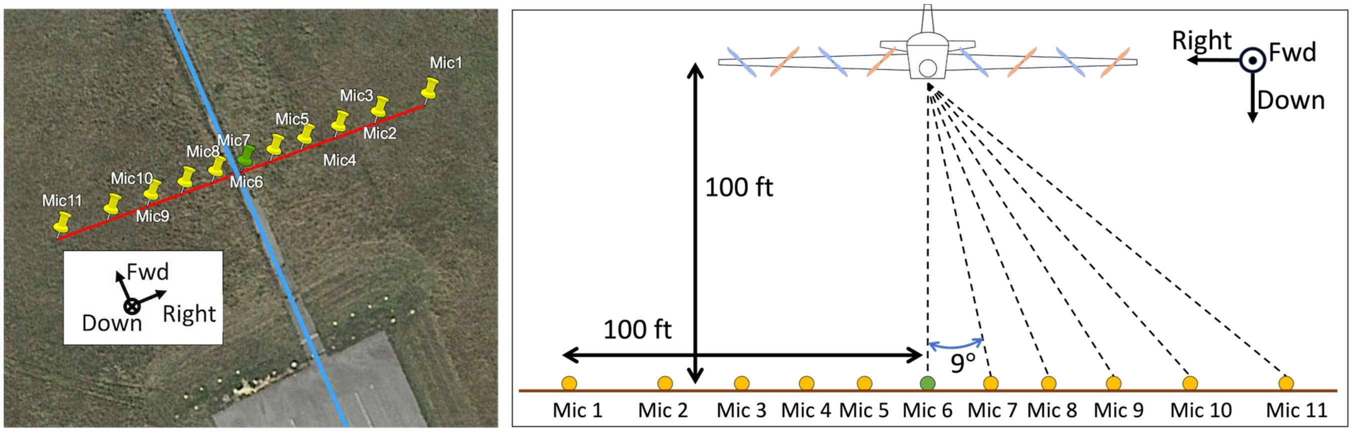


Figure 16. Proposed microphone array configuration with eleven inverted microphones and relative vehicle flight path. Vehicle and microphone spacing are not at scale.

Preliminary Results

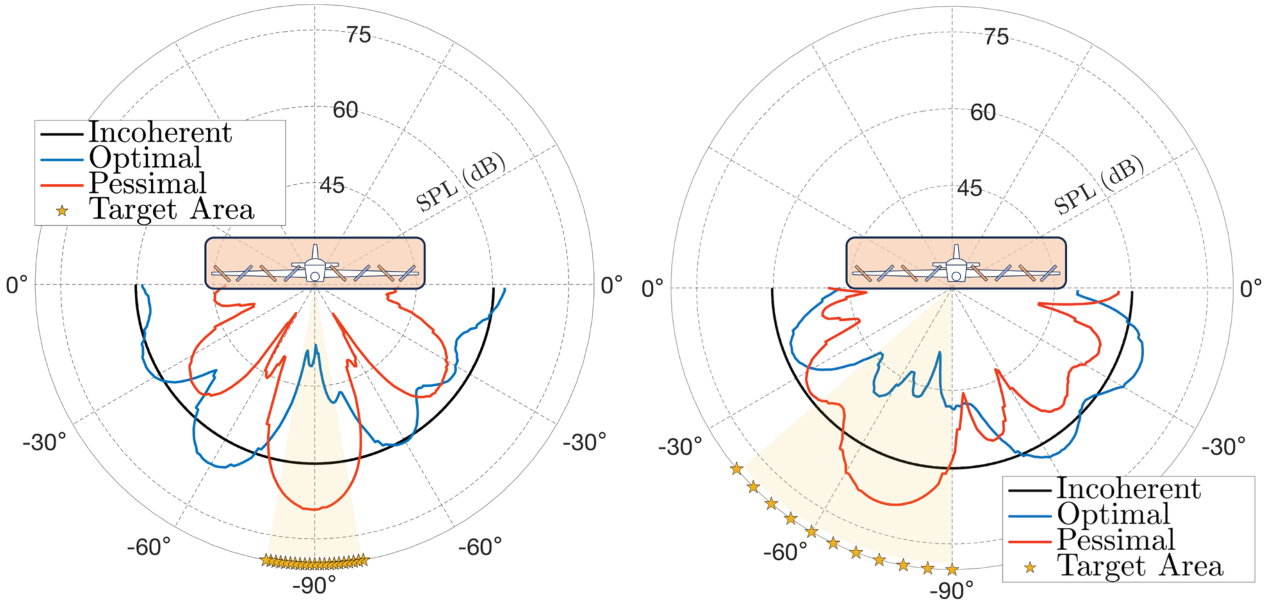
Based on the selected propeller and the prescribed operating condition (~9,000 RPM at ~ 60mph), the time-averaged acoustic pressure over a single revolution was evaluated using PSU-NPS. The PSU-NPS framework couples mid-fidelity aerodynamic modeling through CHARM with acoustic predictions using PSU-WOPWOP. This integrated approach enables an accurate prediction of the noise from the rotorcraft across various flight regimes.

The predicted acoustic signals were subsequently employed as input to an optimization procedure, wherein three different sets of simulated observers were analyzed:

- Symmetric distribution directly beneath: A set of observers distributed beneath the vehicle along a ±20° arc centered on the fuselage axis.

- Asymmetric wide-angle distribution beneath right wing: A set of observers ranging from directly beneath the vehicle to 50° arc to one side.
- Sparse wide-angle distribution: A set of observers sparse in a semicircular span beneath the vehicle.

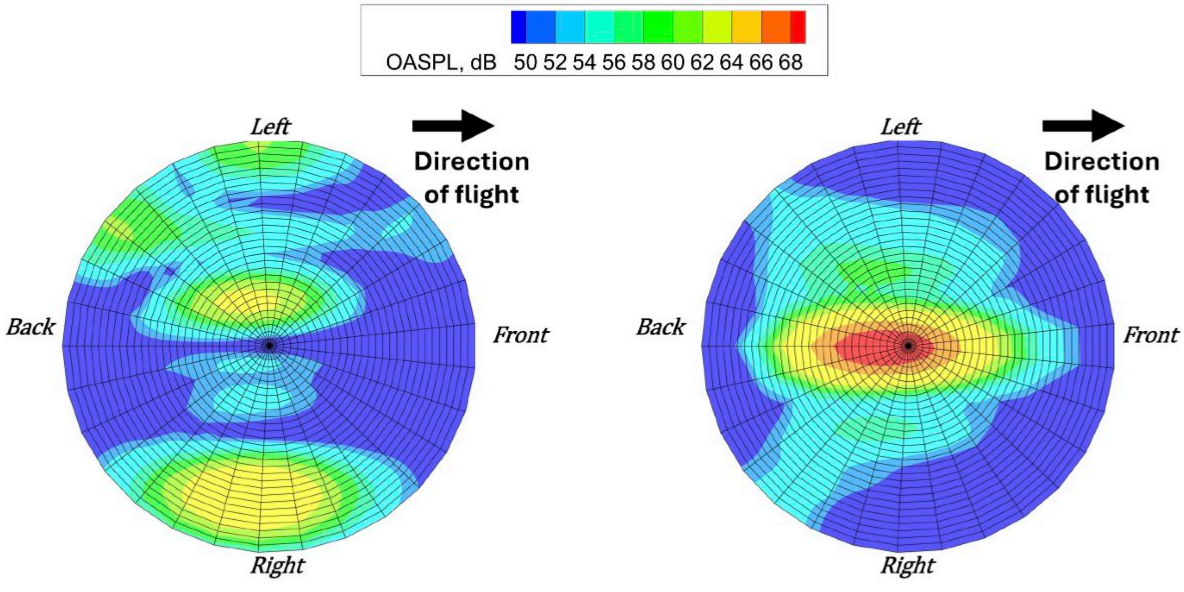
The prediction for the symmetric and asymmetric observer distributions, assuming the vehicle is located directly above the microphone 6 in the microphone array, is illustrated in Figure 17a and Figure 17b, respectively. This prediction accounts exclusively for the tonal component and highlights the overall SPL, as well as the expected attenuation and amplification, due to a different set of relative phases, at and around the specified frequency. The optimal case corresponds to a condition of attenuation, whereas the pessimal case is associated with amplification. This result demonstrates the expected attenuation and amplification obtained through the imposed relative phase distributions, while also evidencing the capability to tailor the radiated noise directivity by appropriately selecting the governing solution. Furthermore, for the symmetric distribution, the results indicate that destructive interference at an elevation of -90° yields an attenuation of approximately 20 dB, whereas constructive interference at the same elevation produces an amplification of about 10 dB, both with reference to the expected incoherent level. For the asymmetric distribution, similar analysis yields an average difference of approximately 18 dB from the pessimal to the optimal case. The optimization process aims to minimize or maximize the SPL within the entire target region; however, the resulting set of phase combinations may produce varying acoustic performance across that region due to differences in the overall phase interaction.



(a) (b)

Figure 17. Prediction slice for the cases with (a) symmetric and (b) asymmetric observer distributions, covering a different set of elevation angles beneath the vehicle.

In addition, using the same set of relative phases for the symmetric observer distribution, Figure 18a and Figure 18b show the stereographic projections of the lower noise hemisphere for the optimal and pessimal cases, respectively, as obtained from CHARM and PSU-WOPWOP when applying the fixed-phase solution determined by the optimization algorithm.

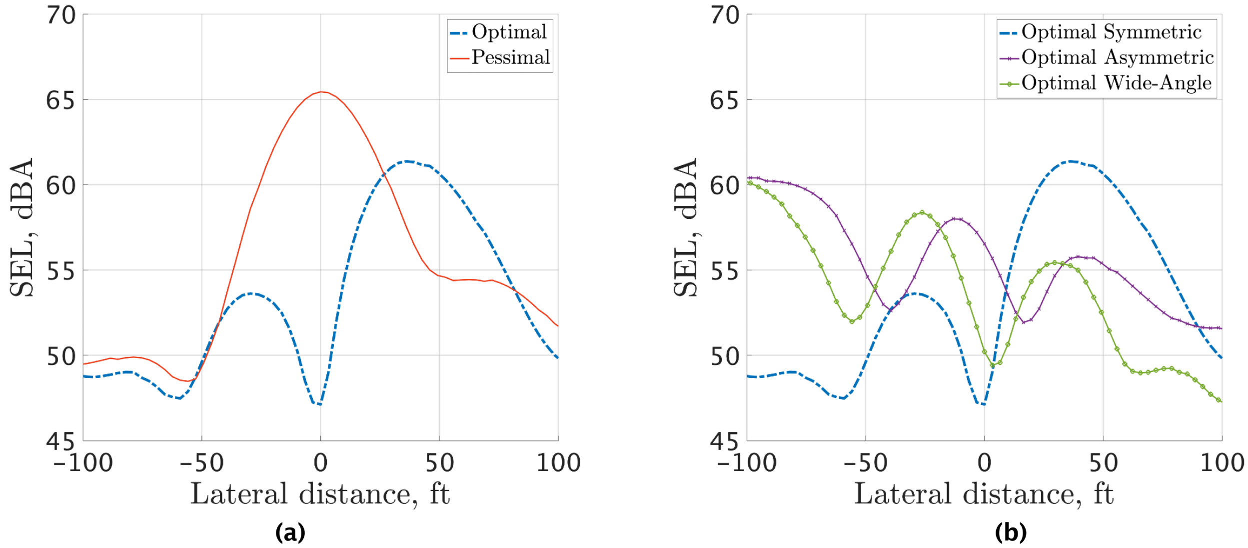


(a) **(b)**

Figure 18. Projection of the lower noise hemisphere, where the center indicates directly below the vehicle and the outer edge corresponds to the vehicle plane. Acoustic predictions from CHARM and PSU-WOPWOP are shown for the optimal (a) and pessimal (b) phase combinations of the symmetric distribution case.

PSU-WOPWOP was also used to investigate a larger observer region to assess the acoustic footprint over an extended area. In this configuration, the vehicle approaches from a distant location, passes directly over the microphone array, and then continues beyond it by an equivalent distance, ensuring symmetry in the flight path relative to the measurement grid. The acoustic impact at the observer locations is quantified using the SEL, which incorporates both the amplitude and duration of the noise event.

The result of SEL analysis versus the lateral distance from the center of the array is presented in Figure 19a and Figure 19b. The first shows the comparison between optimal and pessimal cases for the symmetrical observer distribution case studied, while the second shows the comparison between the optimal condition for all three cases studied.



(a) **(b)**

Figure 19. Predicted sound exposure level (SEL) variation over lateral distance for the (a) symmetric distribution and (b) all three cases.

Publications

Valente, V. T., Greenwood, E., & Johnson, E. N. (2025). An Experimental Evaluation of an Electronic Rotor Phase Synchronization System for Multirotor Aircraft Noise Control. *Journal of American Helicopter Society, 70*(4). https://doi.org/10.4050/JAHS.70.042008

Valente, V. T., Greenwood, E., & Johnson, E. N. (2026). Multirotor Noise Control using Synchrophasing Under Nonstationary Conditions. *Journal of Sound and Vibration, 629*. https://doi.org/10.1016/j.jsv.2026.119673

Valente, V. T., Chaudhary, R., Greenwood, E., Johnson, E. N., & Brentner, K.S. (2026, May 26-29). Predictions and Measurements of Noise Control via Synchophasing for a Fixed Wing Distributed Electric Propulsion Aircraft in Free Flight [Abstract submitted]. 32nd AIAA/CEAS Aeroacoustics Conference, Brussels, Belgium.

Outreach Efforts

The investigation team holds monthly meetings with FAA and an external advisory board consisting of a dozen interested parties from government and industry.

Awards

None.

Student Involvement

Dr. Vítor T. Valente was responsible for preparing the vehicle setup and adapting the method (both hardware and software). Ph.D. candidate Rupak Chaudhary was responsible for the simulation using CHARM and PSUWOPWOP for generation of pressure time series of the selected propeller and noise hemisphere analysis.

Plans for Next Period

The vehicle has been fully assembled; however, flight testing has not yet been conducted. The installation of avionics systems is currently underway, and ground-based tests are being performed to verify the synchrophasing performance. Preliminary simulation results indicate promising capabilities in terms of both attenuation and amplification of the overall sound pressure level. Furthermore, additional simulations are in progress to evaluate the sound exposure level as a supplementary performance metric. For next term, flight testing is expected to happen along with the analysis and presentation of the results in a conference.

Task 7 – Improved Air Data System Integration and Calibration

The Pennsylvania State University

Objective

The objective of this task is to integrate and characterize a new high frequency air-data system—transitioning from the previously used Airmar® 150 WX to the LI-COR® LI-560—on the large reconfigurable UAS platform. This includes calibrating the LI-560 for inflow and installation effects, validating the accuracy and consistency of the calibration results, and utilizing the improved air-data measurements to better understand the influence of ambient wind on multirotor UAS noise measurements.

Research Approach

A review of prior research was conducted to identify a practical air-data solution for multirotor UAS. Conventional pitot systems are unsuitable for these platforms due to low speeds, variable attitudes, and disturbed inflow. Earlier work on multirotor atmospheric sampling relied on sonic-anemometer weather stations, and these showed good agreement with tower and Light Detection and Ranging (LIDAR) measurements in hover. In transitioning from the Airmar 150 WX to the LI-560 TriSonica® Sphere, the LI-560 offered several advantages: true 3D wind-vector measurement, higher sampling rate capability, lower weight, and reduced flow obstruction—making it better suited for measuring inflow around small UAS and for future installation-effect characterization. Although prior studies focused mainly on hover, installation effects during forward flight remain largely unquantified and motivated development of this system.

To address this gap, the LI-560 TriSonica Sphere–based air-data system was integrated into the reconfigurable UAS platform to provide higher frequency 3D wind measurements, temperature, acoustic speed and static pressure. All data are time synchronized using an independent GPS. A custom Raspberry Pi–based logger was developed to record high-rate data to a compact binary file, along with a parallel 1 Hz ASCII summary. A separate post-processing script converts the binary logs into comma-separated value (CSV) and generates diagnostic plots. The LI-560 and electronics were mounted on an elevated structure to minimize rotor-induced inflow.

Milestones

- Develop a robust data-logging architecture using Python.
- Validate sensor functionality and GPS synchronization.
- Conduct Wind-tunnel testing to characterize baseline sensor performance.
- Integrate the LI-560 air-data system as a standalone system on the reconfigurable UAS.

Major Accomplishments

A new air-data system was developed by integrating the LI-560 module with a Raspberry Pi–based data logger and a GPS receiver to ensure alignment with vehicle state information. Wind-tunnel tests were conducted to characterize baseline sensor performance. Planned work includes GPS-assisted upwind–downwind calibration flights, and full characterization of installation effects on the UAS. The integrated system already supports analysis of how wind and airspeed influence multirotor noise during flyover tests, enhancing understanding of UAS noise behavior under varying atmospheric conditions.

Figure 20 shows the wind speed variation over time. The weather station was placed inside the wind tunnel, and wind speed was measured at several throttle settings. At each setting, the throttle was held for approximately 3 mins before being increased to the next level. Wind speed was also measured using two reference methods: (1) a Venturi meter and (2) a static pitot probe.

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® LI-COR and TriSonica are registered trademarks of Li-Cor, Inc., Lincoln, Nebraska.

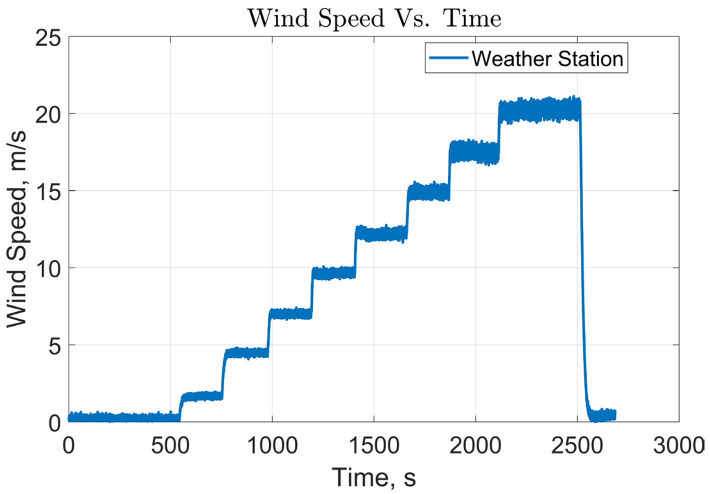

Figure 20. Wind speed time history during test inside wind tunnel.

Figure 21 shows the average wind speed at different throttle settings measured by the weather station, the Venturi meter, and the static pitot probe. The observed error ranges from 3–7%, with a maximum error of 7% occurring at approximately 15 m/s.

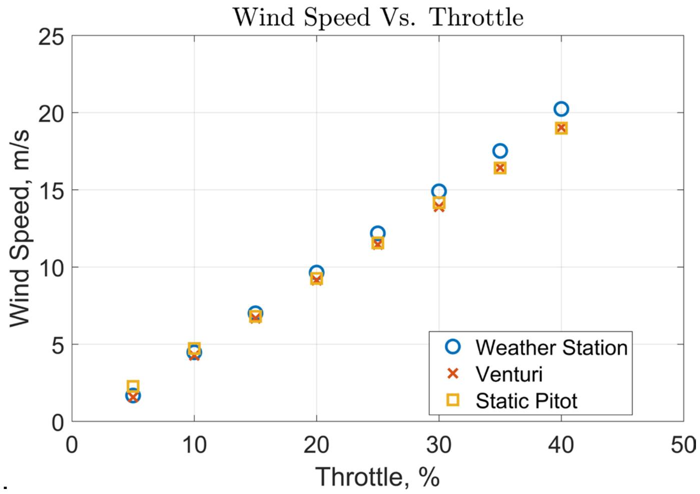

Figure 21. Wind speed at different throttle settings.

Figure 22 shows the wind-speed time history during the throttle-ramp test. The measured trend agrees well with the venturi reference, with discrepancies appearing at higher speeds and a maximum error of approximately 5%.

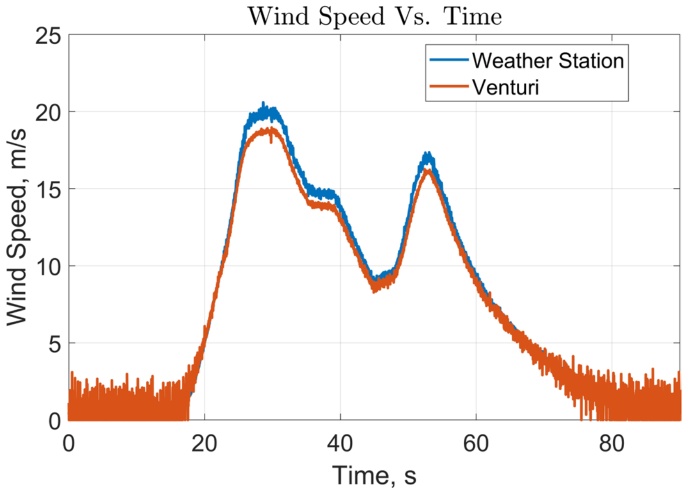

Figure 22. Wind speed time history during ramped throttle.

Figure 23 shows the PSU-hexacopter with the LI-560 TriSonica weather station installed. The sensor is mounted approximately 1 ft above the top plate and about 1.7 ft above the rotor plane. The system is standalone and can be easily removed and installed on the PSU octocopter as needed.

Figure 23. Weather station installed in PSU-hexacopter.

Publications

ElSharkawy, E., Valente, V. T., Rachaprolu, J. S., & Greenwood, E. (2024, July 29 – August 2). *Calibration of an Air Data System for Small Multirotor Aircraft* [Conference Presentation]. AIAA AVIATION FORUM AND ASCEND 2024 (AIAA 2024-4393). Las Vegas, Nevada. https://doi.org/10.2514/6.2024-4393

ElSharkaway, E., Valente V. T., Rachaprolu, J. S., & Greenwood, E. (2024, September 9-11). *Effect of Wind on Multirotor UAS Noise Measurements* [Conference presentation]. QuietDrones 2024 Symposium, Manchester, United Kingdom. https://doi.org/10.17866/rd.salford.27886245.v1

Outreach Efforts

The investigation team holds monthly meetings with FAA and an external advisory board consisting of a dozen interested parties from government and industry.

Awards

None.

Student Involvement

PhD candidate Rupak Chaudhary has been responsible for the development, programming, and analysis of the data produced by the onboard air-data system. Dr. Vitor Valente has provided guidance and mentorship throughout the development of the air-data system.

Plans for Next Period

- Conduct tests to build trust in the air-data system calibration methods.
- Use the calibrated sensor to conduct wind profile measurements at different heights and spatial locations throughout the test site. These data will be correlated to ground-based meteorological measurements.
- Correlate measured air and meteorological data to the aircraft flight state and acoustic data to better understand the effects of environmental conditions on noise generation and propagation.