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

The Pennsylvania State University

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- Tasks:
  1. Computational Modeling of Unmanned Aircraft System (UAS) and Urban Air Mobility (UAM) Configurations
  2. Development of a Source Separation Process (SSP) for Distributed Propulsion Vehicles
  3. Development and Testing of a Reconfigurable Multirotor UAS Vehicle
  4. UAS Noise Measurement and Analysis of Variability
  5. UAM Noise Measurements

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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 UAM platforms violate the steadiness assumption employed in the measurement and modeling of conventional aircraft noise. Rotor or propeller states, such as the rotational speed or blade pitch angle, will vary continuously and independently as the vehicle control system responds to atmospheric perturbations. Many of these vehicles employ 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 will result 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 will vary. 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, there is no longer a unique mapping of the overall flight condition of the vehicle to a corresponding acoustic state. This project aims to develop noise measurement techniques and data analysis methods that can reduce this variability, thereby allowing repeatable characterization of UAS and UAM noise.

Task 1 - Computational Modeling of UAS and UAM Configurations

The Pennsylvania State University

Objective

The goal of this task is to develop computational models of UAS and UAM aircraft to provide a simulated environment in which various noise measurement configurations and data processing methods can be rapidly investigated ahead of acoustic flight testing. During the reporting period, this task was focused on establishing criteria for far-field acoustic measurements of small multicopter UASs.

Research Approach

A computational investigation was conducted to determine the distance of the acoustic far-field for the Tarot X8 octocopter in a hovering flight condition. The far-field distance was found by comparing the sound pressure level (SPL) computed by PSU-WOPWOP—which includes all near-field acoustic terms—to propagation from a compact source by spherical spreading, i.e., the 1/r law. For this research, the far-field distance is defined as the point at which the PSU-WOPWOP prediction diverges from 1/r scaling of the farthest predicted SPL by 0.3 dB. An example of determining the far-field distance for this vehicle is shown in Figure 1. A logarithmically spaced array of observers is placed along a line extending from the center of the aircraft at an azimuth angle of $\psi = 180^\circ$ and elevation angle of $\theta = -60^\circ$. In this figure, the predicted SPL is plotted in blue against a logarithmic scale of the distance in single rotor diameters, $D$. The red dashed line plots the far-field SPL from the farthest observer corrected back to closer distances according to spherical spreading. The two lines begin to diverge in the near-field; the last point at which these lines diverge by less than 0.3 dB is shown by a yellow circle, representing the far-field distance along this ray. Because the observers are located at discrete distances from the center of the vehicle, the divergence from spherical spreading at this location may be less than 0.3 dB in some directions. Figure 2 plots the difference between the predicted and scaled levels, showing how the change in levels begins to increase rapidly as the observer enters the near-field at approximately $5D$. 
Figure 1. Variation in predicted and $1/r$-scaled noise levels with increasing distance. SPL: sound pressure level.

Figure 2. Difference between predicted and $1/r$-scaled noise levels with increasing distance. SPL: sound pressure level.

**Milestone**

The milestone for this task is to develop a computational approach to establish the distance at which microphones must be placed from multirotor UAS and UAM aircraft to ensure that measurements are made in the acoustic far-field of the aircraft.

**Major Accomplishments**

The process described above was repeated for a wide range of azimuth and elevation angles about the center of the aircraft to examine the variation in the far-field distance as the emission angle varies. These data are plotted on a hemisphere, using a stereographic projection of the hemisphere, as shown in Figure 3. The azimuth angle, $\psi$, is plotted azimuthally from 0° at the tail of the aircraft to 180° at the nose, and the elevation angle, $\theta$, is plotted radially, with 0° representing noise radiated in the plane of the rotors at the edge of the plot and -90° representing the noise radiated directly below the vehicle, shown in the center of the plot. The direction used to generate Figures 1 and 2 is shown in blue in Figure 3 for reference. Several parametric studies were conducted using this method to investigate the parameters that affect the far-field distance for small multirotor UASs.
Figure 3. Acoustic hemisphere coordinate system, shown using a stereographic projection. The observer direction used in Figures 1 and 2, located at azimuth $\psi = 180^\circ$ and elevation $\theta = -90^\circ$, is marked in blue.

Far-Field for Different Rotor Noise Sources
PSU-WOPWOP allows the contribution of different generating mechanisms (i.e., noise sources) to be evaluated separately; these include rotational noise sources, thickness and steady loading noise, and broadband airfoil self-noise, caused by turbulent pressure fluctuations on the rotor blades. The far-field distance was determined for each of these noise source mechanisms individually, as well as for the combination of all noise sources. Figure 4 plots stereographic far-field distance hemispheres for both a single rotor and the complete octocopter configuration for thickness, loading, and broadband noise sources. Figure 5 plots the far-field distance for complete prediction including all noise sources.
Figure 4. Variation in computed far-field distance by noise source mechanism.
Figure 5. Computed far-field distance for the combined total of all noise source mechanisms.

For the single isolated rotor, the far-field distance is axisymmetric for all noise sources. The predicted far-field distance is also constant across all elevations for the thickness noise source, i.e., from $\theta = 0^\circ$ shown at the edges to $\theta = -90^\circ$ at the center of the plot. There is a large variation in far-field distance with elevation angle for loading noise, with the distance tending to increase as the observer moves farther out of the plane of the rotors. For broadband noise, the far-field distance tends to reach a maximum distance at an intermediate elevation angle, approximately 20° below the plane of the rotor. Because broadband noise dominates the radiated acoustics for this low-tip-speed rotor (i.e., a tip Mach number of 0.23), the far-field distance for all rotors combined is in close agreement with that of the broadband noise sources alone. Similar results are obtained for the octocopter configuration, except that acoustic interference between the rotors results in an azimuthal variation in the calculated far-field distance for the discrete-frequency (i.e., tonal) noise sources. Four “lobes” of increased far-field distance are observed for the octocopter configuration, where a constant rotation rate of 4,000 RPM is maintained by each rotor.

Table 1 lists the minimum, maximum, and average far-field distances across all emission angles shown on the hemisphere for each noise source and configuration. Very large far-field distances (up to nearly 300 $D$) were computed for loading noise sources. The far-field distance computed for thickness noise is significantly lower, ranging from approximately 8 diameters for a single rotor to approximately 11 diameters for the complete octocopter configuration. The broadband noise has the shortest predicted far-field distances, averaging 3 diameters for a single rotor and approximately 7 diameters for the complete configuration.

Table 1. Minimum, maximum, and average far-field distance for each noise source. D: rotor diameter.

<table>
<thead>
<tr>
<th>Source</th>
<th>Minimum/Maximum (D)</th>
<th>Average (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Rotor</td>
<td>7.9/7.9</td>
<td>7.9</td>
</tr>
<tr>
<td>Octocopter</td>
<td>3.7/16.3</td>
<td>10.7</td>
</tr>
<tr>
<td>Loading</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Rotor</td>
<td>7.9/296.3</td>
<td>170.0</td>
</tr>
<tr>
<td>Octocopter</td>
<td>11.3/296.3</td>
<td>215.3</td>
</tr>
<tr>
<td>Broadband</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Rotor</td>
<td>2.6/3.7</td>
<td>3.0</td>
</tr>
<tr>
<td>Octocopter</td>
<td>2.6/11.3</td>
<td>6.9</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Rotor</td>
<td>2.6/3.7</td>
<td>3.0</td>
</tr>
<tr>
<td>Octocopter</td>
<td>2.6/11.3</td>
<td>6.9</td>
</tr>
</tbody>
</table>
Number of Rotors
Another study was conducted to investigate the effect of changing the number of rotors on the far-field distance of the vehicle. The total noise generated by all sources is used, which is again dominated by broadband noise for this configuration. In addition to the single and octocopter configurations studied in the previous section, a quadcopter and hexacopter configuration are also included. Far-field distance spheres are plotted in Figure 6, and the maximum, minimum, and average values across all directions are tabulated in Table 2. The directionality characteristics are similar for all configurations, as the noise is dominated by the broadband source terms. The computed far-field distance increases as the number of rotors increases, even though the rotor-to-rotor distance remains constant for all configurations.

![Images of single, quadcopter, hexacopter, and octocopter configurations]

Figure 6. Variation in far-field distance with the number of rotors.

<table>
<thead>
<tr>
<th>Number of Rotors</th>
<th>Minimum/Maximum (D)</th>
<th>Average (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.6/3.7</td>
<td>3.0</td>
</tr>
<tr>
<td>4</td>
<td>2.6/5.5</td>
<td>4.2</td>
</tr>
<tr>
<td>6</td>
<td>2.6/7.9</td>
<td>5.7</td>
</tr>
<tr>
<td>8</td>
<td>2.6/11.3</td>
<td>6.9</td>
</tr>
</tbody>
</table>

Table 2. Minimum, maximum, and average far-field distance as the number of rotors is varied. D: rotor diameter.
Publications

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

Awards
None.

Student Involvement
M.S. student Keon Wong Hur is primarily responsible for the development of UAS noise predictions. Specifically, the far-field distance studies were conducted to generalize the definition of the far-field distance of UAS and UAM aircraft. This information will be utilized to inform the design of future UAS and UAM noise measurements. Ph.D. student Rupak Chaudhary has started working with higher-fidelity modeling using the Penn State Noise Prediction System (DEPSim/CHARM/PSU-WOPWOP). These predictions will include the flight dynamics of the vehicle based on the DEPSim multirotor flight simulation code, including the variation in RPM required to track a trajectory. The resulting acoustic predictions will be compared with experimental data from both outdoor acoustic flight test measurements and laboratory experiments conducted under controlled conditions.

Plans for Next Period
The higher-fidelity Penn State Noise Prediction System will be used to develop a more realistic model of multirotor aircraft noise generation, including rotor-rotor aerodynamic interactions and unsteady flight. This system will be used to elucidate the variability of multirotor aircraft noise and to design and validate experimental approaches intended to reduce the variability in experimental characterization of multirotor aircraft noise.

Task 2 - Development of an SSP 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.

Research Approach
The SSP developed in this task is mainly a two-step process that combines a time-domain de-Dopplerization procedure and Vold–Kalman (V-K) order tracking filter. The flowchart in Figure 7 outlines the steps of the SSP. This approach will de-Dopplerize ground-based 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. Moreover, the need to characterize the acoustic directivity of these aircraft demands that the processed data be projected onto an acoustic hemisphere to illustrate the noise radiation patterns.
Figure 7. Flowchart of the system architecture of the source separation process. BPF: blade passing frequency. IDW: inverse distance weighting.

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 data sets. The V-K filtering technique was applied to anechoic wind tunnel acoustic measurements from a coaxial rotor. De-Dopplerization and acoustic hemisphere generation steps were applied to acoustic flyover measurements of the Tarot X8 multirotor aircraft. Once both the de-Dopplerization and order tracking filter procedures were verified, a combination of two steps was used to analyze Bell 430 helicopter flight test data.

**Milestones**

The milestones for this task consist of (a) developing an SSP for stationary acoustic measurements, (b) implementing a de-Dopplerization approach to covert non-stationary measurements to a stationary frame, (c) applying the process to simulated and measured data to evaluate the effectiveness of the separation, and (d) applying the process to multirotor aircraft acoustic measurements to extract acoustic components for each rotor.

**Major Accomplishments**

The effectiveness of the developed SSP approach was tested with three data sets: anechoic wind tunnel measurements of a coaxial rotor setup, acoustic measurements of a Tarot X8 multirotor UAS aircraft, and acoustic flight test measurements of a Bell 430 helicopter. Some results are presented below to highlight the capabilities and limitations of the SSP.

**Acoustic Measurements of a Coaxial Setup in an Anechoic Wind Tunnel**

This data set was used because the rotors were operating at close and crossing rotor speeds, which is similar to rotor speeds observed in multirotor vehicles. The experimental setup included a test stand that held the motors in a coaxial configuration.
A combination of 1/2” and 1/4” Bruel & Kjaer microphones mounted on a curved linear microphone array were used to collect acoustic measurements. The rotor stand included a tachometer along with other instrumentation for performance measurements. The tachometer measured the rotor RPM with high resolution at 131 kHz. The acoustic data were also sampled at 131 kHz; in this way, the acoustic signals were synchronized with the RPM measurement for both rotors to apply the source separation. The experimental setup is shown in Figure 8.

Figure 8. Experimental setup of a coaxial rotor on a test stand in the Penn State anechoic wind tunnel.

The close and crossing rotor rotational speeds of the top and bottom rotors of the coaxial setup are shown in Figure 9. The top and bottom rotor noise components were extracted via the V-K filter of the SSP. Figure 10 presents results in the frequency domain for a time point of 20 s and an elevation angle of -30°. The Original signal is the original acoustic signal measurement from the experiment. The Rotor 1 and Rotor 2 components are the extracted harmonic components of the top and bottom rotors obtained by the V-K filter of the SSP. The Residual component is the leftover component after the extracted Rotor 1 and Rotor 2 components are removed from the original signal. The Residual component is primarily comprised of broadband noise.

Figure 9. Time variation of rotor speeds for the coaxial rotor experiment.
The signal was initially subjected to a high-pass filter to remove any shaft-order tones caused by imbalances in the test stand; thus, there is negligible acoustic energy below 100 Hz. The V-K filter was then applied to extract the rotor tones from the original signal. The results of the extraction are displayed in Figure 10, which shows that the magnitude and frequency of the extracted rotor 1 and rotor 2 signals correspond to the harmonic peaks from the original signal, indicating a clean extraction of rotor harmonic components in the frequency domain.

Figure 10. Spectra of original, residual, and extracted rotor signals for the edgewise forward flight case at a time point of 20 s. PSD: power spectral density.

Acoustic Flight Test Measurements of the Bell 430 Helicopter
The SSP was then applied to measured acoustic flight test data for an instrumented Bell 430 helicopter collected by NASA, Bell, and the U.S. Army. The instrumentation for the flight test included a main rotor shaft encoder, which allowed an accurate measurement of the main rotor rotational speed (RPM). The gear ratio was used to infer the tail rotor RPM from the main rotor RPM measurement, and these RPM readings were used to obtain the blade passage frequencies for both rotors. Using onboard differential global positioning system (DGPS) tracking data, the propagation times were calculated, the acoustic measurements were de-Dopplerized, and the V-K filter was used to extract the first 20 harmonics of the main rotor and the first 10 harmonics of the tail rotor.

The SSP was first applied to steady-state cases to examine the performance with acoustic flyover measurements. For the steady-state cases, the acoustic state of the aircraft is straightforward, and the noise sources do not change rapidly over time. The extracted measurements of the main rotor and tail rotor were used to produce acoustic hemispheres to investigate the directivity of the rotors. The hemispheres for a level-flight case are shown in Figure 11, with the main rotor hemisphere on the left and the tail rotor hemisphere on the right.
Both hemispheres shown in Figure 11 present noise levels normalized to a distance of 100 ft from the aircraft. In the main rotor hemisphere, higher main rotor noise levels can be seen both toward the advancing side of the rotor and directly in front of the aircraft. As shown in the tail rotor hemisphere plot, the noise of the tail rotor reaches a maximum level directly ahead of the helicopter, at an azimuth angle of 180°. The hemispheres for the main rotor and tail rotor agree with the directivity patterns expected from theoretical predictions.

The SSP was then applied to maneuvers to investigate the effectiveness of its application to non-steady-state conditions. A microphone is selected, and the noise characteristics of the helicopter throughout the maneuver are analyzed while measurements are obtained at the observer microphone location. In this case, the condition was a cyclic pitch-up condition initiated at an indicated airspeed of 60 kt. Figure 12 presents a composite plot showing the extracted SPL time histories, observer measurement location, and acoustic pressure time series for selected observer locations during the maneuver.
The presented SPL plots are integrated over a mid-frequency range of 90–470 Hz, which lies between the 4th and 20th harmonic of the main rotor blade passing frequency, to emphasize the blade—vortex interaction (BVI) noise in the extracted signals. The tonal components of both rotors are significantly higher than the residual component. The extracted signal of the main rotor is presented along with the extracted tail rotor signal at three time instants to highlight the different noise sources that are involved during a maneuver. The tail rotor noise is relatively constant throughout the maneuver. The waveforms show characteristic negative peaks associated with the tail rotor thickness noise, which are not expected to vary much with changes in the rotor operating condition.

Acoustic Flight Test Measurements of the Tarot X8 Multirotor UAS

Flight test measurements of the Tarot X8 octocopter were performed at the Mid-State Regional Airport (KPSB) in Philipsburg, PA, as described in more detail in Task 4. Although this aircraft did not have the instrumentation required to measure the rotor speed, an accurate measurement of the aircraft position data was used to apply some components of the SSP. First, the de-Dopplerization step of the SSP was applied, and then, the acoustic measurements were de-propagated to generate acoustic hemispheres.

Figure 13 presents the acoustic hemisphere with the overall SPL (OASPL) metric for a flyover at an altitude of 50 ft and a speed of 10 mph. Figure 14 presents the acoustic hemisphere for the same flyover at an altitude of 50 ft and a speed of 10 mph, but with an A-weighted SPL. The noise hemispheres for both metrics have similar noise “hotspots” under the aircraft. However, there is a difference in the noise levels of the OASPL hemisphere, where the levels are higher in directions closer to the plane of the horizon.
In the OASPL metric hemisphere, there are “lobes” of acoustic energy in the plane of the horizon toward the forward and aft directions at azimuth angles of 30°, 150°, 180°, 210°, and 330°. These observer locations are closer to the horizon of the aircraft, i.e., they are measured at distances further from the aircraft. This variability may be related to acoustic interference of the rotational noise sources (thickness and loading noise) generated by the vehicle, which radiated most prominently in the plane of the rotors. These variations are less prominent in the A-weighted noise hemisphere, which de-emphasizes the lower harmonic tones and is largely determined by the higher-frequency unsteady loading and broadband noise sources.
Publications

Outreach Efforts
The investigation team holds monthly meetings with 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, who intend to use the method to isolate noise generated by a multirotor vehicle in hovering and low-speed flight. Posters presenting this method have been shown at the Penn State Center for Acoustics and Vibration Workshop (October 2021) and at the Vertical Flight Society Forum 78 (May 2022).

Awards
Best Poster Award, Center for Acoustics and Vibration Workshop, October 2021.

Student Involvement
M.S. Student Joel Rachaprolu developed and tested the SSP on computational data and extended the application of the process to helicopter flight test data and baseline UAS measurement data. Rachaprolu is currently working on implementing the SSP on multirotor UAS aircraft with encoded motors.

Plans for Next Period
This task has been completed. However, this process has not yet been applied to multirotor UAS aircraft. Once the SSP is applied to a multirotor UAS with accurate measurements of rotor phase and/or RPM, a more accurate mathematical solution for the filter can be implemented to improve the resolution of the extracted signals. While the hardware for measuring rotor RPM has been validated in the laboratory and installed on the research UAS developed in Task 3, software still needs to be developed to enable recording of the RPM onboard the aircraft.

Task 3 - Development and Testing of a Reconfigurable Multirotor UAS Vehicle
The Pennsylvania State University

Objective
The objective of this task is to design and develop a multirotor UAS vehicle that can be easily reconfigured to explore 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
Both small- and large-sized reconfigurable multirotor UAS aircraft were designed, with a smaller vehicle serving as a testbed for design concepts that were later integrated into the larger and more capable aircraft. Developmental ground and flight testing was performed prior to flights for acoustic data collection. These initial tests have focused on the hexacopter configuration to ensure a higher level of redundancy during initial testing. Onboard instrumentation includes a real-time kinematic DGPS and an inertial measurement unit. This sensor suite also allows a time-accurate position and state estimate that can be correlated to the acoustic measurements.

Milestones
The milestones for this task consist of (a) the identification of acoustically significant configuration changes to be made on the vehicle, (b) initial design of the vehicle and selection of sensors, (c) control system design, and (d) ground and flight testing.
Major Accomplishments
Following initial testing, both vehicles went through a second design iteration based on lessons learned.

Small Reconfigurable UAS
The size of the aircraft was increased to approximately 530 mm, measured from tip to tip of the motor mounts. The new frame retains the capability to handle three motor arm configurations: hexacopter, quadcopter, and tricopter. Carbon fiber was used for the main body, arms, and motor mounts. These configuration changes allow the use of a higher-accuracy real-time kinetic DGPS on the small UAS and support additional onboard research instrumentation. This change also extends the limit on propeller size to 8 inches.

Large Reconfigurable UAS
The size of the large UAS was increased to approximately 1,650 mm from tip to tip of the motor mounts. The reconfigurable characteristics remain unchanged from the original design. An additional level was added to the main body to support additional avionics, including a weather station for airspeed and atmospheric condition measurements during flight. When fully assembled with batteries, the weight of the empty aircraft is 40 lb, which is below the Part 107 limit of 55 lb; however, higher gross weights may be flown with an approved waiver. The maximum propeller size was increased to 32 inches for the hexacopter configuration. Light-emitting diode strips were installed below the arms to indicate the orientation of the vehicle while in flight.

Flight Testing and Acoustic Measurement
After the redesign process, the large UAS was used for acoustic measurements over four different test days and across several different flight conditions, including hover, forward flight, and ascent–descent maneuvers. Photographs of the large UAS in the field are shown in Figure 15. More detailed information regarding these test conditions and preliminary results can be found in the description of Task 4 in this document.

Figure 15. Photographs of the large reconfigurable unmanned aircraft system at Mid-State Regional Airport on the ground (left) and in the air (right).

Publications
Outreach Efforts

The investigation team holds monthly meetings with 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 Georgia Institute of Technology, the University of Salford, Texas A&M University, and the NASA Langley Research Center. Discussions are ongoing about potential opportunities for collaboration.

Awards

None.

Student Involvement

Ph.D. student Vítor T. Valente was primarily responsible for the design, assembly, and configuration of both UASs. He also served as the safety pilot for the UASs during flight testing procedures.

Plans for Next Period

Plans for the following term include acoustic characterization of the small version of the reconfigurable multirotor UAS inside Penn State’s flow-through anechoic chamber. These efforts will include noise measurements made while the aircraft applies a synchrophasing algorithm to steer and reduce the radiated tonal noise. Based on the results of this initial investigation, low-noise control algorithms for outdoor free flight will be developed, and outdoor testing and acoustic measurements will be made. For the large UAS, the team plans to continue collecting acoustic data for different conditions and configurations.

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 measurements 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, surrounded by the Moshannon State Forest and Black Moshannon State Park near Philipsburg, PA. Research noise measurements were made for the Tarot X8 octocopter UAS and the large reconfigurable research UAS described in Task 3. Each vehicle was flown through a range of operating conditions, including hover, forward flight at several speeds, climb, and descent. Flyover testing was conducted at several altitudes, from near ground level to 400 ft above ground level (AGL), in order to evaluate the ability to scale UAS noise measurements made at one flight altitude relative to another, given the relatively low noise levels of small UASs. Acoustic measurements were made with Penn State’s networked, battery-powered, and field-deployable acoustic data acquisition system capable of sampling at up to 125 kHz at 24-bit resolution with subsample accurate 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.

Milestones

The milestones for this task consist of (a) collecting a baseline acoustic, performance, and meteorological data set of UAS noise measurements and (b) analyzing the data to quantify and understand the variability of UAS noise.

Major Accomplishments

Tarot X8 Acoustic Variability Study

Building on the noise measurement approach developed in the previous year of this project, a more extensive data set was collected for the Tarot X8 octocopter, as shown in Figure 16. To assess the noise variability, repeated flyover measurements were conducted for the same nominal flight condition. Acoustic data were collected using a distributed array of microphones, as shown in Figure 17. This array features two lines of microphones perpendicular to the flight track, to capture noise across a range of sideline angles at two different instances in time, as well as a smaller subarray of microphones parallel to the flight track, to capture noise at the same emission angle at four different times during each flyover. Two different microphone installation types were employed, as shown in Figure 18. Inverted ground-plane microphones were located at all
measurement positions. Elevated tripod-mounted microphones were collocated with ground-plane microphones at one centerline and one sideline location.

**Figure 16.** Tarot X8 octocopter.

**Figure 17.** Acoustic array for the unmanned aircraft system at the approach end of Runway 16 at Mid-State Regional Airport. LZ: Landing Zone.
Flyover noise measurements were conducted at a range of altitudes and speeds. For each test point, the vehicle would fly along the flight path in both the “nominal” and “opposing” directions. Numerous repeated test points were collected for each flyover condition. For example, 20 repeated test points were collected for flyover conditions with a flight speed of 20 mph at 50-ft altitude AGL. Figure 19 presents the mean A-weighted SPL time history measured at the centerline microphone location for all 20-mph, 50-ft-AGL flyover flight conditions (solid black line). The grey envelope surrounding the mean represents the variation across the entire set of flight conditions. The variation in SPL ranges from 3 dB at the point where the aircraft overflies the microphone to as high as 8 dB when the vehicle is farther from the microphone. Similar trends are observed for other flight conditions and observer locations, with the greatest variability found for observers far from the aircraft and at emission angles near the plane of the rotors. Integration of the SPL into the sound exposure level (SEL) showed SEL variations ranging from 4 to 7 dBA, with the greatest variations observed for the microphones farthest from the flight track.
Figure 19. Variation in A-weighted sound pressure level (SPL) time histories for 20-mph level-flight flyover conditions at 50 ft above ground level over centerline microphone M3.

A linear, equally spaced microphone array consisting of microphones M10, M12, M11, and M5, which run parallel to the vehicle flight path, was designed to gather noise data for the same flight condition and emission distance at four different instances in time for each run. The schematic in Figure 20 shows how repeated measurements are made at the same angle at different points in time during each flyover. The variation in measured SPL at different time points during a single run is termed the intra-run variability. An analysis was conducted to compare the degree of intra-run variability with the inter-run variability measured at the same microphone across repeated runs for the same flight condition.

Table 3 shows the variation in the peak SPL for 20-mph, 50-ft-AGL flyovers across different runs and sideline array locations. For convenience, entries in the table are color-coded based on the SPL magnitude, with the highest levels coded red and the lowest coded green. For each run number, associated with both a nominal upwind and opposing flight path heading, values are tabulated separately for each direction. No clear trends or biases appear across microphone locations or flight path directions. The bottom row of the table summarizes the mean SPL for each location, along with the minimum and maximum
levels and the corresponding range of levels, representing the inter-run variability. Likewise, the rightmost column provides the same statistics across all microphone locations for each run, representing the intra-run variability.

Overall, the mean SPL for all cases shown in Table 3 was 38.9 dB, with a minimum of 35.8 dB and a maximum of 42.8 dB. Significantly, the range between the minimum and maximum measured values tended to be less within one run (as measured using different microphones) than for the same microphone across all runs. Within a run, the range of SPL variation was 2.2 dB for a single microphone averaged across all runs, whereas the SPL variation averaged across the four microphones and across all runs was 5.0 dB. Consequently, while intra-run variations are significant, they do not entirely explain the variation observed between repeated runs of the same flight condition. This result implies that variability in the flight state during a run has a smaller effect on the variation of noise levels than changes in noise occurring over a longer time scale, e.g., due to changes in ambient atmospheric conditions.

Table 3. Comparison of inter- and intra-run variations in A-weighted sound pressure level. FPH: flight path heading.

<table>
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<tr>
<th>Run</th>
<th>M10</th>
<th>M12</th>
<th>M11</th>
<th>MS</th>
<th>Mean</th>
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<th>MS</th>
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</table>

Another analysis was conducted to investigate the variation in integrated SEL as the flyover altitude of the aircraft was varied. Data for nominal 20-mph flyovers conducted at flight altitudes of 50, 100, and 250 ft are plotted in Figure 21. Figure 21 also presents several curves intended to correct the data back to a 50-ft flyover altitude with the following equation:

\[ L_{AE} = L_{AE_{50}} + C \log_{10} \left( \frac{H}{50} \right) \]

where \( L_{AE} \) is the corrected A-weighted SEL, \( L_{AE_{50}} \) is the average SEL for the 50-ft flyover flight condition, \( H \) is the flyover altitude of the measured data, and \( C \) is a coefficient controlling the scaling of noise from one altitude to another. FAR Part 36 Appendix J provides a flyover altitude correction for helicopters, where \( C = 12.5 \) dB based on experimental measurements. The theoretical correction for an omnidirectional source flying at constant speed corresponds to \( C = 10.0 \) dB. A best fit of the measured data available for the Tarot X8 in this flight condition yields \( C = 8.9 \) dB. However, it should be noted that limited data are available at the highest altitude, where the signal-to-noise ratio is only 15 dBA. Additionally, the high degree of variability in the source noise may significantly affect the best-fit curve. Additional data across a wider range of altitudes should be collected to establish the appropriate altitude correction factor for small multirotor UASs.
Figure 21. Sound exposure level as a function of altitude.

More detailed analyses of the Tarot X8 acoustic measurements are provided in the publications associated with this task, including spectral variations over time in forward flight and hover, a comparison of noise measurements obtained with different microphone installations, and a detailed analysis of directivity variations across repeated flyover conditions.

Large Reconfigurable UAS

Acoustic, weather, and flight state data for over 120 individual test points have been collected for the large reconfigurable UAS during the reporting period, covering a wide variety of vehicle configurations and operating conditions, as listed in Table 4. A photograph of the large reconfigurable UAS on its approach to landing is shown in Figure 22.

Table 4. Test points collected for the large reconfigurable unmanned aircraft system (UAS).

<table>
<thead>
<tr>
<th>Reconfigurable UAV</th>
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<tbody>
<tr>
<td>Hover 13 Hover 6  Hover 0 Hover 69</td>
</tr>
<tr>
<td>Flyover 4 Flyover 9 Flyover 21 Flyover 0</td>
</tr>
<tr>
<td>Descent/Ascent 0 Descent/Ascent 3 Descent/Ascent 0 Descent/Ascent 0</td>
</tr>
</tbody>
</table>
Vehicle state data and local ambient weather data have been collected and correlated to the acoustic data for each test point using GPS time. A preliminary analysis of the acoustic data collected during these tests has been performed. Figure 23 shows a spectrogram of the noise measured for the large UAS in hover at 50-ft altitude AGL at microphone M8, located 200 ft from the hover test point. The rotor tones can be seen to vary significantly in frequency and magnitude as the rotor RPM values are adjusted to maintain a stable hover flight condition.

Figure 22. Full-size reconfigurable unmanned aircraft system (hexacopter configuration) in the landing procedure after one mission.

Figure 23. Spectrogram of a hover flight condition at 50 ft above ground level for the full-size reconfigurable unmanned aircraft system. PSD: power spectral density.
The relationship between the vehicle state and noise variation is currently being investigated. Figure 24 presents the vehicle pitch and roll attitude time histories against the A-weighted SPL for the same recording. It can be seen that the large increase in SPL occurring at approximately 25 s corresponds to a change in the roll attitude of the aircraft.

Figure 24. Sound pressure level (SPL) time histories and attitude of the vehicle (roll and pitch) for the hover condition at 50 ft.

Further data analysis will be conducted to identify other states that could be related to this change and the magnitude and causes of variability in the measured acoustic data. Data for both the Tarot X8 and large reconfigurable UAS are being organized and packaged to simplify the collected noise, weather, and vehicle data into a streamlined database that can be used by the FAA and subsequently the broader research community.

Publications

Outreach Efforts
The investigation team holds monthly meetings with an external advisory board consisting of a dozen interested parties from government and industry. Discussions have been held with the investigation team for ASCENT Project 61 to validate streamlined procedures for UAS noise data collection and analysis. 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 using their auralization and human subject testing capabilities.

Awards
None.

Student Involvement
Ph.D. student Vítor T. Valente and M.S. students N. Blaise Konzel, Joel Rachaprolu, and Sebastian Lopez conducted acoustic flight testing of the Tarot X8 and large reconfigurable UAS. Vítor T. Valente was responsible for the operation and analysis of data collected for the large reconfigurable UAS. N. Blaise Konzel conducted the analysis of acoustic variability for the Tarot X8.
Plans for Next Period
Analysis of data collected during the current reporting period will continue in the next period. These efforts will include the processing of all UAS flyover data into acoustic hemispheres, with an emphasis on characterizing the statistical variability of noise levels emitted over all frequencies and directions. The variation in acoustic characteristics with changes in nominal flight condition will be investigated, including changes in flight speed and flight path angle (i.e., climb and descent). Additionally, a more detailed comparison of differences between data measured using inverted ground-plane and elevated microphones will be conducted, including the changes in spectral quantities and the effect on integrated noise metrics such as the SEL and effective perceived noise level.

The test team will continue to collect data for a wide range of UAS configurations and operating conditions. New array designs will be investigated to help decouple the variations in noise over time from the variations with emission angle. The measured flight state of the reconfigurable UAS will be correlated to measured acoustic data, with the aim of identifying the cause of UAS noise variability and establishing limits on acceptable flight state variation for repeated acoustic characterizations of multirotor aircraft. Additional data will be collected on the variation in noise with flight altitude, including very low altitudes where the microphone may be in the acoustic near-field of the aircraft.

Task 5 - UAM Noise Measurements
The Pennsylvania State University

Objective
The objective of this task is to conduct an acoustic characterization of Beta Technologies’ UAM aircraft.

Research Approach
Test plans were developed to characterize the noise of the ALIA-250 UAM in forward flight and vertical flight operating modes. Plans were also developed for the ALIA-40d subscale model in transition and the prop truck test rig in hover and low-speed forward flight conditions.

Milestone
The milestone for this task consists of collecting a baseline acoustic, performance, and meteorological data set of UAM noise measurements across several operating modes.

Major Accomplishments
Noise measurements of the ALIA-250 UAM aircraft were conducted by the Penn State test team in August 2022, as shown in Figure 25. Data were collected for the aircraft in a conventional takeoff and landing configuration for flyover flight conditions at several altitudes and airspeeds, as well as during takeoff and approach. Six repeated test points were collected for each flyover flight condition, allowing the variability in noise to be assessed. Over 40 individual test points were collected over multiple days of testing. A limited data set was also collected for the prop truck test rig at several RPM values and low-speed forward flight conditions. Aircraft availability and weather prevented full-scale vertical flight and subscale flight noise measurements from being conducted during the current reporting period.
Publications
None.

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

Awards
None.

Student Involvement
M.S. student N. Blaise Konzel developed the test plans. Ph.D. student Vítor T. Valente and M.S. student Joel Rachaprolu conducted the field measurements with BETA Technologies in Plattsburgh, NY.

Plans for Next Period
Noise measurements will be conducted for the full-scale vertical flight and the subscale aircraft in transition in the next reporting period. These data will be analyzed to assess the acoustic characteristics, including noise variability, of UAM aircraft.