ASSURE UAS Research and Development Program Abstract
FAA Research Requirement: Unmanned Aircraft Systems (UAS) Noise Certification **UAS Research Focus Area:** Airworthiness
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ASSURE External Advisory Board Principle Investigator (if applicable): NA
Other ASSURE External Advisory Board (EAB) Performers (if applicable): NA
Classified or Security Related Work: No

EXECUTIVE SUMMARY:

One of the central objectives of this research effort is to collect, process and archive noise signature data from a number of small UAS's (above 55 lb) in various configurations and flight conditions. The experimental setup will target both flyover acoustic measurements in realistic atmospheric conditions and static measurements that will include isolated propellers as well as complete UAS configurations. The flyover acoustic data will be collected either at designated UAS test sites or at Raspet Flight Research Laboratory, Mississippi State University. The static acoustic measurements will be conducted in an advanced anechoic chamber located at the National Center for Physical Acoustics, University of Mississippi. The resulting archive of UAS noise data will assist FAA in developing standards, procedures, and regulatory products related to UAS, and will represent a invaluable source for further validations of analytical and numerical results. Advanced numerical modeling algorithms will be used to process and analyze the experimental measurements. The numerical modeling algorithms and the experimental results will be subsequently integrated in future research to derive UAS noise reduction solutions.

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1. Background

The detrimental effects of noise pollution have provoked increased public attention over the past few decades. There has been significant concern related to noise radiating from various transportation sources having negative effects on people health, in the form of fatigue, stress, aggression, hormonal imbalance, and in some instances hearing impairment. Noise pollution may also interfere with communication, navigation, and reproductive behavior in animals living in close proximity to noise sources. With the advent of increasing the number of operable unmanned aerial systems (UAS) over the next few years, a challenge arises in regard to the effects of the UAS acoustic signature on the environment and people that these machines may pose. For the increasing civil market any noise reduction that can be achieved on these platforms will broaden the range of missions that can be performed in a regulatory environment with, as yet, undefined rules.

Several distinct noise mechanisms contribute to the generation and radiation of noise from UAS propellers. Based on the frequency content, there are two main classes: tonal (or discrete) and broadband noise. Tonal noise is related to the aerodynamics and kinematics of the blade in uniform flow, and can be further classified as thickness, loading and quadrupole noise. Broadband noise is more complex and is generated by the interaction between the flow and various components of the blade, such as leading edge, trailing edge, or blade-tip, or by the turbulent flow present in wakes. In the present design of many UAS, the propeller is rear mounted and thus operates in a pusher rather than a tractor mode. With a pusher-type propeller, an important portion of the overall noise is generated by rotor interaction with the time-dependent flow distortions that are generated by the upstream components of the vehicle (e.g., the wakes generated by the fuselage and wings).

Research is needed to fully understand the differences in acoustic signatures between manned and unmanned aircraft to determine whether noise certification procedures designed for manned aircraft are appropriate for unmanned aircraft. It may be appropriate for the FAA to develop supplemental test procedures for UAS below a certain maximum take-off weight. Given the expectation that UAS will be sold and operated across borders, it is important for early recognition and coordination regarding noise certification of UAS. FAA's Office of Environment and Energy (AEE) is supporting the Unmanned Aircraft Systems (UAS) Integration Office to ensure the safe, efficient, and timely integration of UAS into the United States' National Airspace System (NAS). In order to fulfill this mission, the FAA is developing standards, procedures, and regulatory products related to UAS. The primary control over aircraft source noise is the noise certification process, and this requires a detailed analysis of the noise signature radiating from different systems. This research effort will assist FAA in fulfilling the above core issues.

2. Scope

The scope of this work is to conduct noise measurements of UAS under 14 CFR Part 36, Noise Standards: Aircraft Type and Airworthiness Certification requirements (14 CFR Part 36) and additional flyovers measurements to support modeling. To this end, the effort under this proposal is targeted to collect, process and archive UAS noise for various systems that are in use today. The experimental data will be used to assist FAA in developing standards, procedures, and regulatory products related to UAS. In addition, a second focus of this effort will be to study the noise radiating from typical UAS propeller, which is believed to be the main source of UAS noise. Numerical modeling will accompany the experimental effort in an effort to identify viable noise reduction solutions. In summary, we aim at answering the next important research questions:

1) What are the differences between noise signatures radiated from manned and unmanned aircraft?
2) How different would the regulatory standards for UAS be compared to the existing standards that apply to manned aircraft?
3) What is the contribution of the propeller noise in the overall noise radiating from a typical UAS that is operated by propellers?
4) What is the minimum altitude a UAS of a certain size can fly to comply with existing noise regulations?
5) How can the noise radiating from a typical UAS be reduced?
6) Would existing aircraft noise reduction techniques work for small UAS?

This research will address gaps in knowledge that are related to UAS noise. The research described in the tasks below will support the following specific requirements:

1. Ensure compliance with 14 CFR Part 36.
2. In addition to 14 CFR Part 36 requirements, include measurements of UAS fly-overs.
3. The size of the UAS used to measure noise will exceed 55 lbs.
4. Initial development of a database to enable modeling of UAS operational noise.

The technical monitor or a representative as designated by AEE will be present for the flight test as an observer. The tasks to be completed within the overall research effort are:

- **Task 1:** Conduct a literature review to validate research.
- **Task 2:** Develop a detailed flight test plan for the research. This will include identification and performance capabilities of the UAS. A sample flight test plan will be provided by AEE.
- **Task 3:** Begin developing a noise database for modeling purposes in consultation with AEE.
- **Task 4:** Develop extensive UAS noise database to assist FAA in developing standards, procedures, and regulatory products related to UAS
- **Task 5:** Explore and derive UAS noise reduction techniques using integrative numerical-experimental approaches.

The research team will provide the test plan to the test site and the UAS operator to review and comment prior to the start of testing.

3. Research Framework

3.1 Research Requirements

The proposed research will target acoustic measurements of UAS in flyover and static conditions. The flyover acoustic measurements will be carried out at designated UAS test sites or at Raspet Flight Research Laboratory (RFRL), Mississippi State University, while the static acoustic measurements will be conducted in an advanced anechoic chamber located at the National Center for Physical Acoustics (NCPA), University of Mississippi. Specific equipment will be acquired under this research project in order to collect complex flyover acoustic measurements.

The research plan is split into four phases that will be accomplished along two years; the technical aspects associated with these phases are described below.

3.1.1 Phase I

SCOPE: Perform a literature review, acquire the necessary equipment, and conduct a few preliminary measurements of UAS noise signature. FAA personnel will witness the noise tests.

TASKS:

- Conduct a detailed study of previous UAS acoustic measurements, either in flyover or static conditions:
    - Literature Review (FAA, and other worldwide agencies)
    - Prepare a technical report that contains the following data:
        - UAS Type
        - UAS Design Type Data
        - UAS Operations:
            - Altitude vs. Speed
            - Operating Environment
            - Mission Type
- Purchase the necessary equipment from Bruel & Kjaer Company, consisting of:
    - 2250-G4 Hand-held Analyzer with Sound Level Meter, Frequency Analysis, Enhanced Logging and Sound Recording Software (Qty: 2). Characteristics of the Type 4189 microphone:
        - Sensitivity: 50mV/Pa
        - Frequency: 6.3Hz . 20 kHz
        - Dynamic Range: 14.6 . 146 dB
        - Temperature: .30 to +150Åã C (.22 to +302Åã F)
        - Polarization: Prepolarized
    - Cable, Microphone, circular-1B 7-pin (F) to circular-1B 10-pin (M), 3,0m(10ft),max.+90°C (194°F) (Qty: 2).
    - Sound Calibrator Class 1 and LS, 94 and 114 dB, 1 kHz
    - 1/2" Pressure-field Microphone, 3 Hz to 20 kHz, 200V Polarization (Qty: 2). Characteristics of the Type 4192 microphone:
        - Sensitivity: 12.5mV/Pa
        - Frequency: 3.15 Hz . 20 kHz
        - Dynamic Range: 19 . 162 dB

        - Temperature: .30 to +300Åã C (.22 to +572Åã F)
        - Polarization: 200V
    - Laptop to acquire and post-process the data.
- Setup the equipment and run a test measurement at RFRL.
    - A representative from Bruel & Kjaer Company will travel to RFRL and present the equipment to the project personnel. A test measurement will be performed on an existing UAS in static conditions.
- Conduct few preliminary measurements at test sites.
    - Type of UAS: Navmar TigerShark UAV (or, similar UAV in consultation with FAA/AEE)
    - Test sites: NUAIR
    - Number of measurements: 2
    - Duration of measurements: 3 days

    - For phase I, the Northeast UAS Airspace Integration Research Alliance (NUAIR) has been identified as the test site, where the initial acoustic measurements will be conducted.

    - *NUAIR Statement of Work:*

        The Griffiss UAS Test Site will conduct a flight test meeting 14 CFR Part 36 requirements, together with measurement of UAS fly-over noise. To meet the project budget, the flight test will be performed on a date selected by the Griffiss UAS Test Site at a time when the flight test UAS is available at the Griffiss Test Site.
    - The test site (in general) will:
        - Make available and ready for flight the UAS;
        - Make available pilot(s) at test site on the assigned day of testing;
        - Meet with the Performer at the test site and understand the flight procedures required for the test period. ASSURE will provide desired flight procedures in advance for the test site's review;
        - Assist the Performer in installing a small GPS device test UAS or utilize a UAS with GPS tracking capability for precision measurements;
        - Have the pilot keep in close communication with the Performer test director regarding the aircraft's position during the testing;
        - Have the UAS become airborne and perform a planned series of flyovers, takeoffs and landings over the Performer microphone stations (see Figure 1);
        - Land the UAS and consult with the test conductors in a debrief meeting.

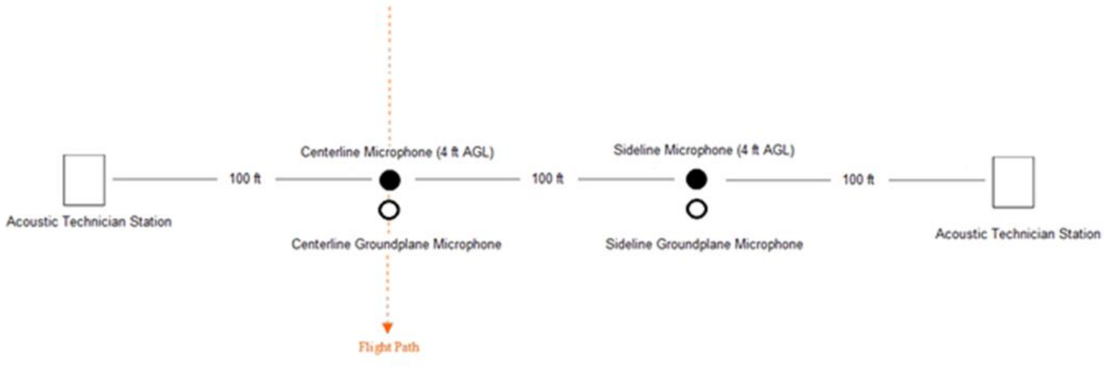

Figure 1. Measurement Microphone Stations

- For flyover noise measurements, two microphones will be distributed at the ground level. They will be spaced 100 ft apart and from the data acquisition equipment. Each microphone will be mounted on a vertical pole located 4 ft above the ground and will be equipped with a windsock device. The flyover measurements will consist of passes up and down the runway at various speeds. We plan to collect acoustic measurements from a number of UASs, featuring both fixed-wing configurations and rotorcraft.

- Technical Review Meeting with FAA Technical Monitors to set the stage for the next phases.

DELIVERABLES:

- First set of UAS noise measurements of a typical UAS with gross weight ranging from 55 lb to 300 lb;
- Technical Report: the progress on UAS Noise Collection.

3.1.2 Phase II

SCOPE: Collect acoustic signature from a number of UAS's in different flight conditions. This phase is a continuation of the work performed in phase I.

TASKS:

- Setup the equipment.
- Conduct multiple acoustic measurements at test sites.
  - Type of UAS: TBD
  - Test sites: TBD
  - Number of measurements: 10
  - Duration of measurements: 30 days
- Start preliminary analysis of the experimental data.
- Technical Review Meeting with FAA Technical Monitors.

DELIVERABLES:

- UAS noise measurements for different systems and flight conditions;
- Technical Report: the progress on UAS Noise Collection.

3.1.3 PHASE III

SCOPE: Collect acoustic signature from a number of UAS's in different flight conditions. Part of the work performed under this phase is a continuation of the work pertaining to phases I and II. In addition, several numerical modeling investigations of the noise radiating from UAS will be conducted.

TASKS:

- Setup the equipment.
- Conduct multiple acoustic measurements at test sites.
    - Type of UAS: TBD
    - Test sites: TBD
    - Number of measurements: 7
    - Duration of measurements: 21 days
- Continue the analysis of the experimental data.
- Initiate numerical modeling with respect to predicting the noise radiating from small UAS.
- Technical Review Meeting with FAA Technical Monitors.

DELIVERABLES:

- UAS noise measurements for different systems and flight conditions;
- Preliminary results from numerical modeling on some canonical configurations;
- Technical Report: the progress on UAS Noise Collection.

3.1.4 PHASE IV

SCOPE: Collect acoustic signature from a number of UAS's in different static conditions, and improve numerical algorithms to predict UAS noise. Validate numerical results using experimental measurements.

TASKS:

- Setup the equipment.
- Conduct multiple static acoustic measurements of UAS propellers in an advanced anechoic camber.
    - Type of propellers: TBD
    - Characteristics of the anechoic camber:
        - dimensions: 5.8 m × 6.1 m × 2.5 m (L-W-H);
        - 3-axis traversing system for instrumentation;
        - temperature, barometric, and psychrometry instruments;
    - Number of measurements: 30
    - Duration of measurements: 30 days
- Analysis of the experimental measurements from UAS propellers.
- Validate numerical algorithms by comparing the numerical results with experimental results.
- Derive UAS noise reduction techniques and test them in the anechoic camber.
- Technical Review Meeting with FAA Technical Monitors.

DELIVERABLES:

- UAS noise measurements for different systems and different static conditions;

- Provide UAS noise reduction solutions.
- Technical Report: the progress on UAS Noise Collection.

3.1.5 NOTES

Static measurements will be conducted both in open air on the runaway and in an advanced anechoic chamber. Using the hub of the propeller as a reference point, the microphones will be spaced 25 ft away from the aircraft. Noise data will be collected for all microphones simultaneously and for four different engine rotation speeds. Each microphone will be pointed in the direction of the aircraft and will be located approximately 4 ft above the runway surface. The indoor acoustic measurements will be performed in an advanced anechoic chamber located at NCPA. The dimensions of the anechoic space are 5.8 m × 6.1 m × 2.5 m (L-W-H) with excellent acoustic performance above 200 Hertz. A 3-axis traversing system is available for positioning instrumentation relative to the sound source. A microphone arc is attached along the back wall of the room, covering a range of angles from 45° upstream of the propeller hub to 160° in the downstream direction. The arc radius at the microphone diaphragm is 2.8 m, centered at the nozzle exit. The room is instrumented with temperature, barometric, and psychrometry instruments to collect the information required for acoustic corrections. Noise from isolated UAS propellers will be also measured in the anechoic chamber, with the objective to derive noise reduction solutions.

3.2 RESEARCH MAPPING

- This research would support the development of modified and/or new regulations, standards, and guidance 14 CFR Part 36.
- This research project will perform acoustic measurement studies of UAS as requested by the FAA. The acoustic measurements to be conducted under this research project will be subsequently used by FAA to define standards, procedures, and regulatory products related to UAS noise.
- Through extensive modeling and experimental studies, the research effort will also deliver UAS noise reduction solutions.

3.3 RESEARCH REVIEW

Very few studies exist in the area of collecting noise from UAS either in static or flyover mode. Worth to mention is the study of Massey and Gaeta [5] who conducted acoustic field measurements of tactical UAS to characterize the noise at various altitudes, power settings, and flight paths. Several studies exist in the area of propeller noise. A number of research groups performed experimental work to characterize and reduce the noise radiated by various classical aircraft or UAV propellers (e.g., Germain et al. [1], Leslie et al. [3], Sinibaldi and Marino [6], Gur and Rosen [2], or Massey and Gaeta [4]).

3.4 REFERENCES

[1] Germain, P., Guo, J. and Hodgson, M. Experimental Study of propeller-aircraft run-up noise, Canadian Acoustics, Vol. 29, pp. 21-27 (2001).
[2] Gur, O. and Rosen, A. Design of a quiet propeller for an electric mini unmanned air vehicle, Journal of Propulsion and Power, Vol. 25, pp. 717-725 (2009).
[3] Leslie, A., Wong, K.C. and Auld, D. Experimental analysis of the radiated noise from a small propeller, Proceedings of 20th International Congress on Acoustics, ICA (2010).

[4] Massey, K. and Gaeta, R., Experimental analysis of UAV-propeller noise, AIAA Paper 2010-3854 (2010).
[5] Massey, K. and Gaeta, R., Noise Measurements of Tactical UAVs, AIAA Paper 2010-2010-3911 (2010).
[6] Sinibaldi, G. and Marino, L. Experimental analysis on the noise of propellers for small UAV, Applied Acoustics, Vol. 74. pp. 79-88 (2013).

4. Period of Performance/Projected Schedule

	MONTHS											
PHASE I	1	2	3	4								
Review of previous UAS acoustic measurements												
Purchase the equipment												
Setup the equipment and run a test measurement												
Conduct few preliminary measurements at test sites												
Review Meeting with Technical Monitors												
PHASE II					5	6	7	8	9	10	11	12
Setup the equipment												
Conduct multiple acoustic measurements at test sites												
Start preliminary analysis of the experimental data												
Review Meeting with Technical Monitors												
PHASE III	1	2	3	4	5	6	7	8	9	10	11	12
Conduct multiple acoustic measurements at test sites												
Continue the analysis of the experimental data												
Initiate numerical modeling												
Review Meeting with Technical Monitors												
PHASE IV	1	2	3	4	5	6	7	8	9	10	11	12
Conduct multiple static acoustic measurements												
Analysis of the experimental measurements												
Validate numerical modeling algorithms												
Derive UAS noise reduction techniques												
Review Meeting with Technical Monitors												

5. Key Personnel

Mississippi State University:
Ratan Jha, Professor and Director RFRL -
Adrian Sescu, Assistant Professor,
Calvin Walker, Senior Flight Test Engineer,
Mark Janus, Associate Professor,
David Thompson, Professor,

University of Mississippi, NCPA:
Nathan Murray, Research Assistant Professor,

Biographies of key PI's:

Dr. Ratan Jha (Director, RFRL and Professor of Aerospace Engineering): Dr. Jha is a Fellow of the American Society of Mechanical Engineers and an Associate Fellow of the American Institute of Aeronautics and Astronautics. His research interests are structural health monitoring, modeling of composite and smart structures, adaptive control of structural vibrations, and unmanned aircraft systems. His contributions include both theoretical and experimental research, which have resulted in over 110 publications in international archival journals and refereed conferences. He has served as advisor to 30 graduate students (including 6 current students) and has served as a committee member for 18 PhD/MS students. He has received research grants totaling $4 Million (with Co-Investigators) from the National Science Foundation, AFOSR, NASA, US Army, and other organizations. Dr. Jha is a Member of AIAA Adaptive Structures Technical Committee, Voting Member of ASTM F38.01 subcommittee on UAS Airworthiness, and Founding Member of ASME Nondestructive Structural Monitoring and Diagnosis Technical Committee. He is an Editorial Board Member for International Journal of Aerospace Engineering and International Journal of Unmanned Systems Engineering. He has served as Technical Chair and General Chair for AIAA/ASME/AHS Adaptive Structures Conference in 2013 and 2014, respectively. Dr. Jha has held leadership positions in both academia and industry. As Director of RFRL, he reports to the Dean of Engineering and works closely with the Vice President for Research & Economic Development. He is responsible for providing leadership and managing all aspects of RFRL operations, including physical, fiscal, and human resources. Dr. Jha served as Assistant/Associate Professor of Mechanical & Aeronautical Engineering at Clarkson University during 1999-2012, where he received Faculty Research Award and Teaching Excellence Recognition. He has taught undergraduate and graduate courses in Aircraft Structures, Engineering Design Methodology, Aircraft Stability and Control, Aircraft Performance, Intro to Aeronautical Design, and Intro to Unmanned Aircraft Systems. Prior to his academic career, Dr. Jha worked at Hindustan Aeronautics Limited (Bangalore, India) for 12 years as engineer/deputy manager/manager and led a team of engineers working on combat aircraft design.

Dr. Adrian Sescu is currently an Assistant Professor of Aerospace Engineering at Mississippi State University (MSU). Previously, he was a postdoctoral fellow at Johns Hopkins University where he conducted research in turbulence and environmental flow. Dr. Sescu's research interests include transition in boundary layers, computational aeroacoustics and turbulent flows. He published over 45 journal articles and conference proceedings in these areas, and made numerous presentations at various national and international conferences. He worked as an instructor at the Department of Aerospace Engineering, Polytechnic University of Bucharest, where he taught Fluid Mechanics and Aerodynamics and conducted research in aerodynamics and computational fluid dynamics. He also worked at Straero Aerospace Institute, Bucharest, where he was involved in projects related to unsteady aerodynamics and aeroelasticity. He received the ASEE SFFP Award in 2013 and 2014, and spent two summers at AFRLA/RQVA where he studied the boundary layer receptivity. He is a senior member of the AIAA, member of ASME, APS, and Sigma Gamma Tau (Aerospace Engineering Honor Society).

6. MSU Facilities Overview

Raspet Flight Research Laboratory is located in Starkville, Mississippi and consists of two large hangers. Each hanger has offices, vacuum/high pressure air, overhead hoists, and high-speed Internet in addition to large work areas for aircraft. Additional facilities include a paint shop, composite storage and fabrication rooms, machine shop, CNC machines, ovens, autoclaves, an engine test room, an electronics shop, and a structural test area. RASPET is the largest and finest equipped university flight research facility in the country.

The world's first all-composite (glass fiber) aircraft, MARVEL (Mississippi Aerophysics Research Vehicle with Extended Latitude), was developed at RFRL as a U.S. Army project and test flown in 1965. HondaJet, the very first all-composite (carbon fiber) small business jet, was designed, built, and tested at RFRL by Honda and MSU personnel in the early 1990's. RFRL fabricated a 50 ft. long stitched wing for Boeing (1999-2000) in collaboration with Seemann Composites (inventor of Seemann Composites Resin Infusion Molding Process or SCRIMP).

Figure 1. Raspet Flight Research Laboratory - Buildings I and II.

The two RFRL buildings (Figure 1) include over 90,000 square feet of hangar, office and machine shop, CNC machines, ovens, autoclaves, and a structural test area. The RFRL has large static test fixtures for testing wings and fuselage sections (Figure 2). There is a high-rate, two-input vibration testing setup for evaluating the vibration characteristics (natural frequencies, mode shapes, damping ratios) of composite parts, such as aircraft wings and fuselage.

Composite structures production capabilities (Figure 3) at RFRL include two autoclaves (large - 10' diameter by 55' length at 300 psi at 850º F and small - 2' diameter by 4' length at 300 psi at 850º F); 10' by 10' walk-in oven; heated platen press - 17"x17"x6" at 100 psi and 600º F; refrigerated storage at 0-40º F for composite material systems; digital data acquisition and control software and computers for the cure monitoring and control of composite parts; designated climate control area for pre-preg and wet lay-up of graphite, Kevlar, and fiberglass components; and fully equipped machine shop for complex structure precision jigging and assembly, which includes an 8' x 16' 5-axis CNC milling machine.

Instrumentation for wave propagation measurements at RFRL include signal generator, power amplifier, PZT actuators/sensors, and a laser vibrometer (Figure 4). The vibrometer can perform non-contact measurement of vibration or wave motion signals at up to 250 kHz frequency, as required for structural health monitoring experiments. A hand-held ultrasonic C-scan NDE equipment has been procured recently. Several desktop computers with 3.4 GHz Intel Core i7th CPU and 16 GB memory are available at RFRL. In addition, MSU's High Performance Computing Collaboratory (an evolution of NSF Engineering Research Center for Computational Field Simulations) has several high performance computing facilities, including Shadow (Cray CS300-LC; 322 TFLOPS; 2640 processors; 15,600 co-processors - Xeon Phi; 8 TB of core RAM), which is currently ranked 185 in the Top500 in the world and 11th among the US Academic Institutions.

Center of Advanced Vehicular Systems (CAVS) unit is designed for cross-disciplinary efforts, helping to promote synergistic research collaboration, and comprises a 47,000 sq. ft. building, currently undergoing a 10,000 sq. ft. expansion, that is located in the Mississippi Research and Technology Park just north of the MSU main campus in Starkville, Mississippi (figure 2). Several of our facilities have video classrooms, affording the use of video equipment in classroom settings and allowing the production of video-recorded classes or live transmission to remote sites as well as network-based instruction. The facilities house a desktop infrastructure of general-purpose workstations and high performance servers for faculty, staff, and student use. An immersive CAVE-like virtual environment facility (consisting of four ten-by-nine foot projected stereoscopic display surfaces, motion tracking, and voice-recognition) provides virtual reality research capabilities.

Figure 2. Center of Advanced Vehicular Systems building at Mississippi State University

The HPC2 is one of the largest university-owned computing centers in the world, providing substantial high performance computing resources for use by its member centers. This includes a 322 TerraFlops liquid-cooled supercomputer featuring over 18,000 Intel Xeon processors (PHI 5110P and E5-2860), a 34 teraFlops 3072 processor Intel Westmere cluster with quad data-rate InfiniBand, a 10 teraFlops 2048 processor AMD Opteron cluster, and numerous additional special purpose machines. Data storage capabilities include a 600-terabyte high performance disk system and a 9-petabyte near-line storage system. Many of our researchers are also heavy users of supercomputers at installations around the country. Our high-performance network backbone utilizes 10-Gigabit Ethernet (10 Gb/s), Gigabit Ethernet (1 Gb/s), ATM OC12 (622 Mb/s), and ATM OC3 (155 Mb/s) technologies. The backbone equipment consists of two Extreme Networks BlackDiamond 6808 switches, one Extreme Networks Summit 7i switch, twenty Extreme Networks 48si switches, six Extreme Networks Summit 200 switches, and one Marconi/FORE Systems ASX-1000 ATM switch. Desktop systems are connected via 100 Mb/s or 1 Gb/s ethernet.

Disk storage is provided via high-performance RAID-enabled disk systems, including a

Sun Microsystems-based SAN storage system. A total of nearly 65 Terabytes of disk space is available for HPC2 researchers. In addition to the online disk space, a Sun StorageTek SL8500 tape library provides a capability of nearly 2 Petabytes of near-line storage. The HPC2's high-performance network backbone incorporates a mixture of 10 Gigabit Ethernet (10Gb/s) and Gigabit Ethernet (1Gb/s) via two Extreme Networks BlackDiamond 6808 switches, an Extreme Networks Summit 7i switch, multiple Extreme Networks Summit 400 and Summit 48si switches. All desktop systems are connected via switched Gigabit Ethernet or 100Mb/s ethernet.