Overview of the Research Aircraft for eVTOL Enabling techNologies (RAVEN) Activity

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The Research Aircraft for eVTOL Enabling techNologies (RAVEN) activity is a collaboration between Georgia Tech and NASA to design and develop a 1,000 lb gross weight class eVTOL research aircraft. The vision for RAVEN is that the aircraft will serve as a "flying laboratory" for enduring research and technology development applications across the realm of eVTOL technologies. A major goal of RAVEN is to disseminate the aircraft design geometry and data from flight tests for the benefit of the broader aeronautics community. Initial research applications will include flight dynamics, controls, acoustics, and automation/autonomy. The aircraft is based on the airframe of a fixed-wing experimental homebuilt airplane that will be modified to incorporate a distributed propulsion system, battery system, fly-by-wire flight control system, and avionics to enable remotely piloted operation. The aircraft is being designed to use commercial off-the-shelf components to the maximum extent practicable to save costs and to accelerate the development schedule without compromising the goal of publishing design geometry and test data. The RAVEN activity is also focused on workforce development by training the next generation of aerospace engineers in eVTOL technologies.

I. Introduction

A wide variety of passenger-carrying electric vertical takeoff and landing (eVTOL) aircraft are currently being developed by the aerospace industry [1], and several companies are in the process of certifying eVTOL aircraft with the FAA and international regulatory agencies [2]. Although progress is being made in eVTOL development, most work carried out by industry is necessarily proprietary in nature. Correspondingly, the research community does not have access to, or the ability to publish, flight test data and other experimental measurements about current eVTOL aircraft designs. Relevant data, including aircraft geometry and the results of wind tunnel and flight tests, are vital for purposes such as validating computational tools, formulating new design methods, and developing novel control strategies.

Some flight research for eVTOL aircraft has focused on subscale testing with small, unmanned aircraft systems (sUAS). These aircraft are typically operated under the restrictions of 14 CFR Part 107 [3], which limits the aircraft gross weight to less than 55 lb and the aircraft speed to less than 100 mph. The small scale of sUAS and the limitations to their flight envelope imply that aerodynamic and dynamic similitude with passenger carrying eVTOL aircraft cannot readily be obtained. For example, from a similitude perspective, it is necessary to match parameters such as disk loading, wing loading, rotor tip speeds, wake structures, component Reynolds numbers, and Froude number between a small-scale aircraft and the corresponding full-scale aircraft throughout the flight envelope. Matching all the relevant similitude parameters via subscale testing is challenging, often requiring different test vehicles for different types of measurements. This challenge of similitude correspondingly limits the applicability of sUAS as flight research/demonstrator aircraft relevant to full-scale configurations. Additionally, due to the limitations of commercial off-the-shelf (COTS) components for hobby radio-controlled aircraft and commercial drones, most VTOL sUAS are controlled in hover by varying motor speed (RPM control),

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whereas passenger carrying eVTOL vehicles are anticipated to predominately incorporate control by varying rotor blade pitch (collective control). For these reasons, the applicability of sUAS flight testing to research in acoustics, flight dynamics and controls for larger eVTOL aircraft is limited.

To address these shortcomings, Georgia Tech and NASA have initiated the Research Aircraft for eVTOL Enabling techNologies (RAVEN) activity. The goal of RAVEN is to design, develop, and flight test a 1,000 lb gross weight class eVTOL research aircraft and to disseminate the aircraft geometry and test data to support the research community. The scale of the aircraft has been selected such that test data would be relevant in terms of similitude to larger passenger-class eVTOL aircraft, and to provide adequate size, weight, and power for research payloads including sensors and data acquisition systems.

The aircraft is being designed to use COTS components to the maximum extent practicable to accelerate the development schedule and to reduce development cost and risk. The aircraft structure is based on the airframe of a fixed-wing experimental homebuilt airplane, and components for the distributed propulsion system, battery system, avionics, and flight control system are being sourced from existing products available from partners and vendors. The aircraft configuration has been chosen to be representative of eVTOL aircraft currently being developed in industry, with relevant technical challenges.

The RAVEN activity is intended to support research in eVTOL flight dynamics, controls, acoustics, and automation/autonomy relevant to advanced air mobility (AAM) passenger aircraft. In the area of flight dynamics and controls, the RAVEN activity will offer the opportunity to develop control laws, to characterize transition from hover to forward flight (and vice versa), to assess aerodynamic interactions, and to explore control allocation in nominal and failure cases for an aircraft with propulsion and actuator redundancy. In the area of acoustics, flight test measurements corresponding to known airframe and proprotor geometry will enable the calibration of computational aeroacoustics tools and contribute to development of new noise metrics. In the area of automation and autonomy, RAVEN will enable the exploration of intelligent contingency management techniques, data fusion, and perception in a relevant environment in terms of vehicle size, computing and sensing capabilities, and operational profile. Furthermore, RAVEN will enable computational tools development and discipline-coupled research across a wide spectrum of AAM-related research interests, complementing NASA’s investments in the Urban Air Mobility (UAM) Reference Vehicle concepts (Fig. 1.)

Another goal of the RAVEN activity is workforce development of future engineers in electric aircraft technologies and VTOL aircraft design and development, a need recognized by the Vertical Flight Society in a recent white paper about the vertical lift workforce [4]. Since inception of the RAVEN activity, twenty-seven Georgia Tech undergraduate and graduate students have been involved, supported by two early-career research engineers. Students have participated in designing, fabricating, integrating, and testing both subscale and full-scale RAVEN components, subsystems, and flight prototypes. Exposure to full-scale electric propulsion components and the integration challenges of a larger scale electric aircraft is atypical for student academic experiences in aircraft design, which typically focus either on paper studies, fundamental research, and/or only subscale designs implemented with hobby-grade components. Furthermore, the collaboration between Georgia Tech and NASA enables Georgia Tech students to work closely with NASA researchers. The technical leadership positions on the NASA team are primarily held by early-career researchers, leveraging NASA experts to mentor both the NASA and Georgia Tech teams.

Quadrotor

Quiet Single Main Rotor

Side-by-Side Helicopter

Lift+Cruise VTOL

Tiltwing

Tiltduct

Fig. 1 NASA UAM reference vehicle concepts [5].

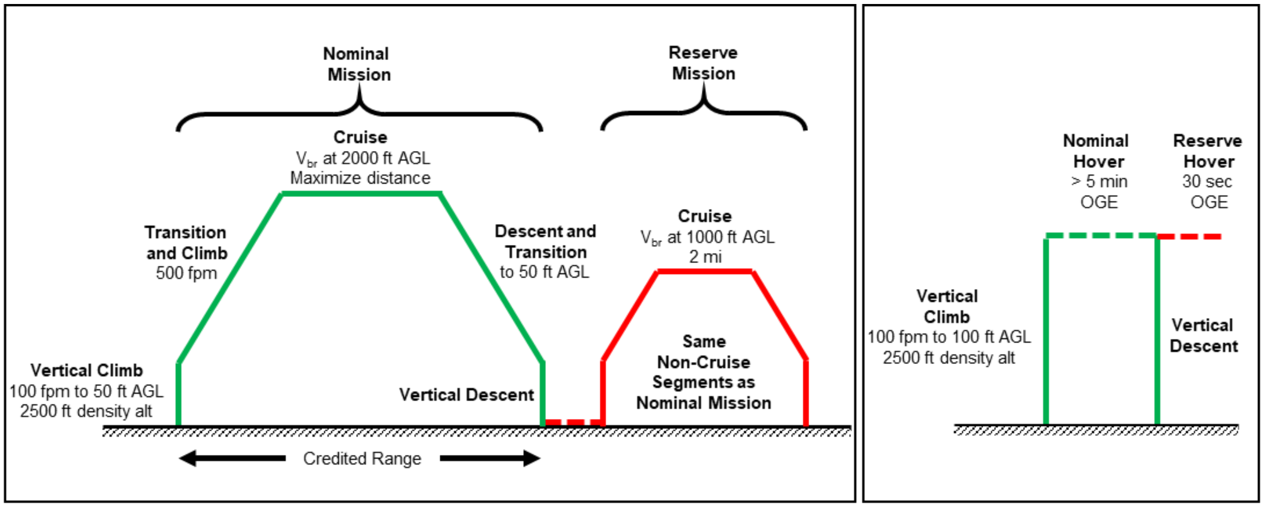
II. Research Applications and Requirements

At the beginning of the activity, Georgia Tech worked collaboratively with NASA to understand research interests within the Aeronautics Research Mission Directorate (ARMD) that could be supported by the RAVEN aircraft. Through this process, the following three research applications were identified as high priority:

- Acoustics: Facilitate acoustical measurements during flight tests with a vehicle of relevant configuration and relevant scale to enable: (1) calibration of acoustics tools developed by ARMD for novel VTOL aircraft configurations, and (2) acoustical measurements in support of development of new noise metrics relevant to AAM [6]. To the maximum extent possible, assure that the aircraft and proprotor geometry can be shared openly and published to facilitate dissemination to the broader aeronautics community.
- Flight dynamics, controls, and interactional aerodynamics: Facilitate flight dynamics and controls research for eVTOL aircraft involving: (1) transition/conversion from hover to forward flight and vice versa, (2) distributed propulsion with propulsor and actuator redundancy, and (3) strong aerodynamic interactions between proprotors, rotors, wings, and/or other aerodynamic surfaces. To enable reasonable dynamic and aerodynamic similitude, this application requires an aircraft with relevant configuration and relevant scale to AAM vehicles under development by industry.
- Automation/autonomy: Facilitate flight research related to contingency management, perception, and data fusion algorithms in a vehicle with a relevant operational profile and with relevant scale to support the size, weight, and power of computing and sensing capabilities of larger AAM aircraft.

A common element in these research applications is the importance of an aircraft with relevant scale. Discussions with NASA researchers have indicated that an aircraft with a gross weight of approximately 1,000 lb or more is required to achieve the flight dynamic, aerodynamic, and acoustic behaviors broadly consistent with those of larger, passenger-class AAM vehicles. The decision to develop the RAVEN aircraft by modifying a single-seat fixed wing airplane situates the aircraft at this scale and provides the relevance needed for these research applications while minimizing aircraft cost and complexity.

These research applications, as well as programmatic and safety considerations, were used to develop reference missions and requirements for the RAVEN aircraft. The reference missions are shown in Fig. 2, and a summary of the identified requirements is provided in Table 1.



VTOL Cruise Reference Mission
(a)

Hover Reference Mission
(b)

Fig. 2 RAVEN Reference Missions.

Table 1 Summary of RAVEN Aircraft Requirements

Requirement	**Rationale**
Tip speed of propellers/rotors in all phases of flight: *Threshold: < 550 ft/s. Goal: 450 ft/s*	Relevance to passenger-class eVTOL acoustics
Collective pitch control of propellers/rotors: *Bandwidth available for attitude control during hover*	Relevance for passenger-class eVTOL acoustics and flight control
Endurance in hover reference mission, OGE, 2500 ft. density alt: *5 mins*	For hover acoustics measurements and flight dynamics characterization
Range in VTOL cruise reference mission, 90% of new battery capacity, balked landing, 2 mile reserve: *> 20 miles*	For overflight and sideline certification noise measurements and transition flight dynamics characterization
Contingencies: *Failure of any one powertrain component does not compromise attitude trim, steady flight power requirements, and maneuver margins in any flight phase*	Safety
COTS components: *Used to the maximum extent possible*	Cost and schedule

Extending beyond the initial research applications discussed above, the RAVEN aircraft is intended to be an enduring test asset that can serve as a “flying laboratory” to support future research and technology development related to eVTOL and other distributed electric propulsion (DEP) aircraft. Potential future research applications include:

- Electric propulsion system and battery energy storage system operational characterization, including thermal management, electromagnetic interference, and component degradation
- Multidisciplinary Design Analysis and Optimization (MDAO) for distributed electric propulsion and eVTOL aircraft design, with a focus on optimizing the entire DEP system—ranging from batteries to motors to proprotors—for the RAVEN airframe and mission
- Support for certification and standards development for eVTOL and DEP aircraft by characterizing flight control approaches, failure conditions, and component and system reliability
- Concepts of Operations for integration of highly automated eVTOL aircraft into the National Airspace System.

III. Design Configuration and Specifications

One of the primary objectives of the RAVEN activity is to minimize development costs and time. To support this objective, the decision was made to develop the RAVEN airframe by modifying a single-seat, homebuilt, fixed-wing airplane originally intended for piloted operation with an experimental airworthiness certificate. The basic airframe structure would be reinforced to fit a DEP system suitable for VTOL operation and for transition to forward flight, while retaining the configuration of the primary aerodynamic surfaces (wings, empennage, etc.) of the original airplane. Consistent with the goals of minimizing cost and development time, components for the DEP system—including propellers, electric motors, inverters, batteries, and cabling—as well as other aircraft subsystems and components—such as control surface actuators and avionics—would be sourced from vendors as COTS items.

After exploring multiple homebuilt airplane kits available on the market, the decision was made to base the RAVEN aircraft on the airframe of the Bede BD-6, shown in Fig. 3a. The BD-6 has a high, cantilevered wing with a 20 ft span that provides adequate ground clearance to facilitate wing-mounted propellers in a DEP eVTOL configuration. The BD-6 has an aluminum space-frame fuselage construction and a tubular aluminum wing spar, as shown in Fig. 3a and Fig. 3b, respectively. Wing ribs are epoxy bonded to the spar, and all skins are bonded to the wing ribs and fuselage frame. These construction methods simplify fabrication, allowing faster and easier assembly compared to riveted aluminum or composite construction. Additionally, analysis has shown that the high stiffness and strength of the tubular wing spar offers the ability to carry the additional loads associated with DEP integration. Georgia Tech has acquired a BD-6 partially assembled by a homebuilder for structural testing and component integration. This airframe includes a rolling fuselage frame and assembled wings and empennage surfaces. The rolling fuselage frame and wing of the BD-6 owned by Georgia Tech are shown in Fig. 3b and 3c.

Fig. 3 Bede BD-6 [7]. (a) BD-6 aircraft, (b) Rolling fuselage frame owned by Georgia Tech, (c) Tubular spar and bonded rib wing owned by Georgia Tech.

Conceptual design studies were conducted for the RAVEN aircraft with different DEP system architectures integrated with the BD-6 airframe. Considering the goal of achieving a relevant configuration to many of the larger passenger-class eVTOL aircraft being developed in industry, the decision was made to focus on configurations in which at least some of the propulsors tilt during the transition from hover to forward flight. Although more complex than configurations such as lift+cruise designs and multirotors, tilting propulsor configurations offer richer opportunities in terms of the research questions that can be addressed through flight testing.

Three DEP architectures—6-rotor, 8-rotor, and 12-rotor configurations—were investigated. For the 8-rotor and 12-rotor configurations, propulsors were situated in pairs, with each pair consisting of one propulsor forward of the wing and one propulsor aft of the wing, and both propulsors affixed on a longitudinally-oriented boom mounted to the wing. The front propulsors tilt from the hover configuration, in which the plane of the rotor is approximately parallel to the plane of the wing, to a forward flight configuration in which the plane of the rotors is in the typical orientation of propellers for a fixed-wing airplane. The aft propulsor on each boom does not tilt and is permanently oriented as a lifting rotor which can optionally be stopped in forward flight. The 6-rotor configuration has three pairs of propulsors: a pair of tilt-capable propulsors forward of the wing, a pair of fixed lifting propulsors aft of the wing, and an additional pair of tilting propulsors situated at the wing tips. Configurations based on these three architectures are shown in Fig. 4. Battery packs are located in the fuselage in each of the configurations and the nose cowling of the BD-6 is envisioned to incorporate avionics in place of a piston engine.

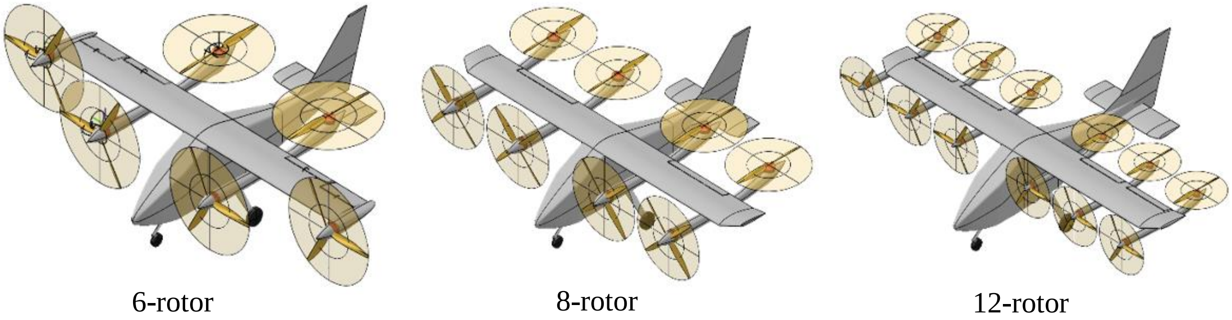


Fig. 4 DEP architectures evaluated for RAVEN (shown in cruise configuration).

Georgia Tech evaluated the availability of COTS components for each of the three DEP configurations. This evaluation involved a thorough exploration of available electric motors, inverters, propellers, and batteries. The results indicated that the 6-rotor configuration allowed for the use of a size class of electric motors and inverters that is available commercially and that has been employed in a variety of eVTOL prototypes in industry. Additionally, the scale of the 6-rotor configuration allows the use of lightweight composite COTS propellers produced for the Light Sport Aircraft (and experimental homebuilt aircraft communities. The 8-rotor and 12-rotor configurations require the use of smaller motors and inverters, many of which do not offer desirable features such as sinusoidal commutation.

For these reasons, as well as its superior performance in conceptual design studies, the 6-rotor configuration was selected as the baseline configuration for the RAVEN aircraft for further design and development. The baseline configuration is shown in Fig. 5 and specifications of the baseline aircraft are shown in Table 2.

IV. Program Overview

The RAVEN activity was initiated in 2020 through a Cooperative Agreement between Georgia Tech and NASA facilitated by the National Institute of Aerospace. The following sections provide an overview of the various activities undertaken by the teams at Georgia Tech and NASA in support of the RAVEN activity.

A. Requirements Definition, Conceptual Design, and Supplier Discussions

At project inception, the period from September 2020 to September 2021 focused primarily on requirements definition, conceptual design, evaluating COTS component options, and instigation of risk reduction activities. Discussions with NASA stakeholders and researchers were held to establish a definitive list of NASA research objectives and requirements for RAVEN, a summary of which is presented in Section II. Conceptual design studies were performed based on these research objectives and requirements, in parallel with discussions with potential COTS component suppliers. The results of the conceptual design studies and supplier discussions led to the selection of the baseline 6-rotor RAVEN configuration shown in Fig. 5 which was presented during a conceptual design review briefing in March 2022.

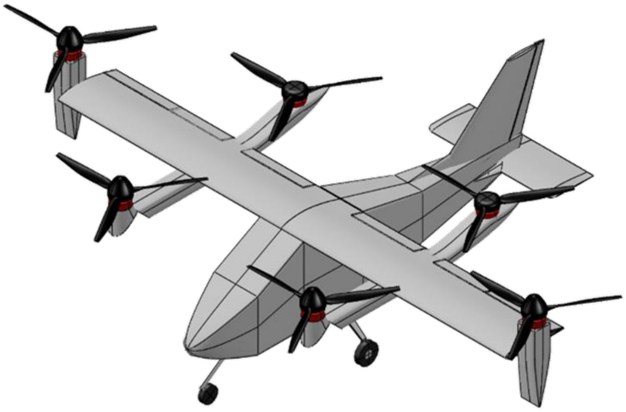


Fig. 5 RAVEN aircraft baseline configuration.

Table 2 RAVEN Aircraft Baseline Specifications

Parameter	Value	Units
Wingspan	20	ft
Length	13	ft
Propeller diameter	5.68	ft
Gross weight	1140	lb
Disk loading	7.5	lb/ft^2
Wing loading	21.5	lb/ft^2
Payload	50	lb
Range (VTOL)	20	nmi

As part of the conceptual design activity, Georgia Tech developed a series of models and simulation tools for the RAVEN aircraft. These models include an OpenVSP [9] model of the baseline configuration, shown in Fig. 5. The OpenVSP model includes accurate geometry of the airframe and propellers, developed using CAD models provided by Bede Aero and the propeller manufacturer, and internal component placement based on dimensions of COTS components for the powertrain, control, and thermal management systems. A mass properties analysis was conducted using the OpenVSP model and bill of materials, along with verification of airframe component mass achieved by weighing the wings, empennage, and rolling fuselage frame of the BD-6 acquired by Georgia Tech. The OpenVSP model has also been used for forward flight aerodynamics analysis using the OpenVSP parasite drag tool, VSPAERO [9], and AVL [10]. In addition, an NDARC [11] model of the RAVEN configuration has been developed which includes a rotor model for the propellers developed in CAMRAD [12] by NASA. The NDARC model has been used to simulate reference missions for RAVEN including the hover mission and VTOL cruise mission, where the VTOL mission includes transition to and from wing-borne forward flight. Finally, a 6-degree of freedom (DoF) flight dynamics model of the baseline RAVEN aircraft has been developed in MATLAB/Simulink. The 6-DoF simulation implements the mass properties and fixed-wing aerodynamics models obtained from the OpenVSP model, and an aerodynamics database based on isolated proprotor performance as predicted by the DUST vortex particle code [13]. An interface has been developed to link the 6-DoF model to a flight simulation in X-Plane [14] for visualization, so that the aircraft can be piloted with a joystick to investigate pilot interfaces and inceptor mapping strategies.

B. Flight Investigation in Conversion and Hover (FINCH) Aircraft

Following the selection of the 6-rotor configuration, a subscale version of RAVEN was designed and built at Georgia Tech. Named the Flight Investigation in Conversion and Hover (FINCH) aircraft, the 22 lb subscale version was developed at an approximately 30% geometric scale of the RAVEN configuration. This activity was undertaken to develop toolchains for control law integration and system identification studies of the RAVEN configuration. Moreover, the activity provided a low-cost, low-risk platform for students to gain hands-on experience with developing a DEP system and conducting flight test campaigns. FINCH was constructed with components including propellers, motors, and electronic speed controllers typically used for radio-controlled (RC) aircraft flown by hobbyists and with a fuselage and empennage from a foam RC scale model of a Cessna 172. A custom wing to accommodate the DEP system and associated tilt mechanisms was designed and fabricated. During development, elements of the DEP system and tilt mechanisms were subjected to significant ground testing and wind tunnel testing, revealing challenges with structural dynamics that were overcome by component re-design as needed. A Pixhawk with Cube Orange Autopilot [15] was implemented with the ArduPlane VTOL flight control software [16], and an experienced RC test pilot operated the aircraft remotely. FINCH was flown in hover and low-speed flight in a series of flight tests, with both fixed and tilting propeller mounts installed, to conduct systems identification using a methodology developed at NASA [17]. Entirely student led, the development of the FINCH aircraft created collaboration channels between Georgia Tech and NASA which will be leveraged during the development of the RAVEN aircraft. The tilting propeller installations of the FINCH aircraft and an image of the aircraft in flight are shown in Fig. 6**.**

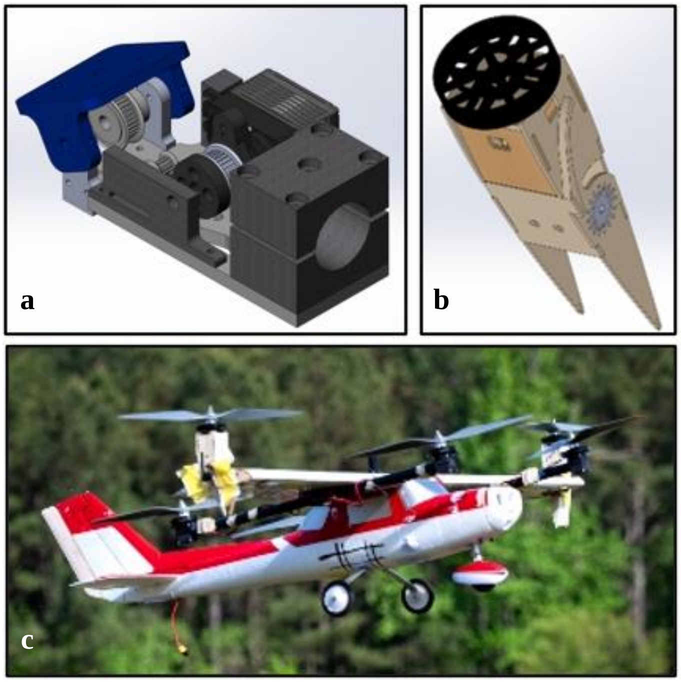


Fig. 6 Development and flight testing of FINCH. (a) Front rotor tilt mechanism design, (b) tip tilt rotor nacelle design, (c) FINCH in flight.

C. Electric Powertrain Test Stand

For static testing of full-scale components for the RAVEN DEP powertrain including propellers, motors, and inverters, an electric powertrain test stand was developed at Georgia Tech. The test stand consists of a welded steel frame to support a propeller and motor installation, with the propeller axis oriented horizontally. The frame is sized for testing propellers up to 6 ft diameter and to measure thrust and torque loads up to 350 lb_f and 1650 lb_f-in, respectively. To power the electric motor, the test stand incorporates a high-voltage (up to 500 VDC) electrical system including a 54 kW programmable DC power supply, a pre-charge circuit, high-voltage contactors, circuit protection, and emergency stops. Instrumentation includes a 6-axis load cell to measure propeller forces and moments, voltage and current sensors, and associated data acquisition systems. Control of the inverter and power supply is achieved through a CAN bus, with a custom LabView implementation for controlling the system and recording measurements. A 40-kW electric motor, suitable for use as a motor for RAVEN, with an associated inverter were procured for evaluation on the test stand. To support cooling of the inverter, a liquid cooling loop consisting of a radiator, pumps, and water reservoir was designed and integrated.

Test stand integration was completed in summer 2022 and no-load operations were performed for system testing. Development work on the test stand is continuing, with a focus on additional calibration and system testing in the coming months. Fig. 7 shows the integrated test stand and several of the system components. Additional details associated with the development of the test stand are provided in Ref. 18.

Fig. 7 Powertrain test stand. (a) Fully integrated test stand with motor and inverter, (b) 54 kW DC power supply (c) high-voltage electrical components including contactors, fuses, and current and voltage sensors, (d) data acquisition and control components.

D. Preliminary Structural Analysis of the Airframe and Propeller

To study the feasibility of using the BD-6 as the baseline airframe for RAVEN, a preliminary structural analysis of the airframe was conducted by the team at Georgia Tech. This analysis focused on assessing anticipated static loads, including bending and torsion on the wing spar associated with nominal and motor-out operations in hover, transition, and maneuver. The structural analysis was initially conducted using analytical beam models which was followed by finite element modeling (FEM) in Abaqus [19]. The mesh for the FEM model was developed from the BD-6 CAD model provided by Bede Aero. As a result of the static loads analysis, a simple design was performed for structural reinforcement of the wing spar at the fuselage attachment junction. This reinforcement reduced predicted stresses in the most critical load cases to acceptable levels.

In addition, propeller structural testing was pursued due of uncertainties in how the propeller, which was designed for fixed-wing airplanes, would operate in edgewise and transition flight of the RAVEN aircraft. The goal of the structural testing was to infer the distribution of flexural rigidity along the radius to enable aeroelastic modeling in CAMRAD. The first aspect of the approach was the development of an optimization algorithm that adjusts the coefficients of a polynomial model of the EI distribution within the Euler-Bernoulli beam equation, subject to measurements of blade tip displacement when different loading conditions are applied along the blade. Next, an experimental apparatus to measure blade tip deflections under various loading conditions was designed and fabricated. Blade deflection measurements were taken, and the optimization model was used to estimate EI distributions. Presently, additional measurements and refinement of the approach are being carried out. Fig. 8 illustrates examples of the work conducted in the structural analysis and testing task.

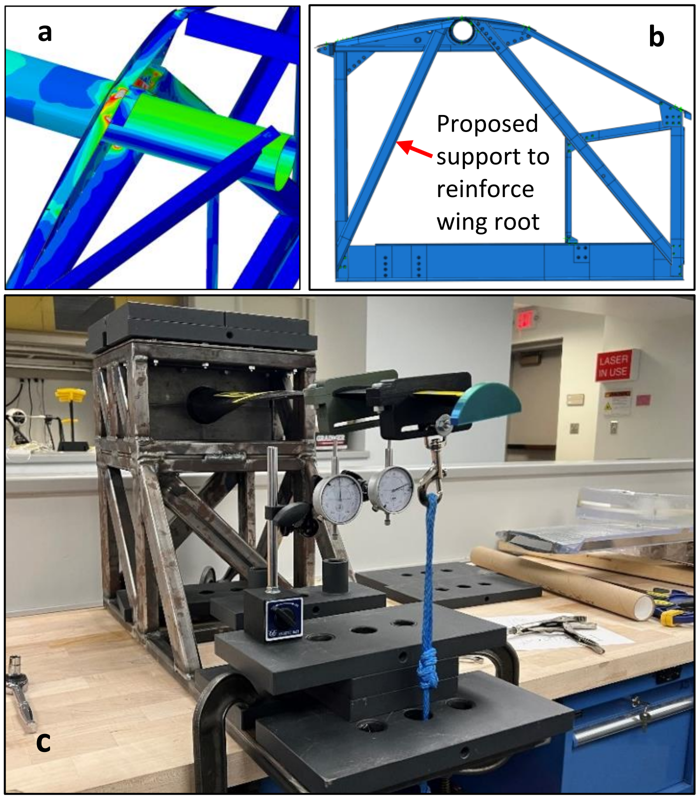


Fig. 8 Structural analysis and tests. (a) FEM analysis indicating need to reinforce wing, (b) proposed wing root reinforcement to reduce stresses, (c) propeller blade bending test rig with blade.

E. Subscale Wind Tunnel and Flight Test (SWFT) Aircraft

To facilitate the development of the control laws and flight dynamics model of the RAVEN aircraft, as well as to advance flight dynamics and controls research, the team at NASA developed the Subscale Wind Tunnel and Flight Test (SWFT) aircraft. The ultimate objective was to apply NASA's "Learn-to-Fly" [20] research to enable rapid in-flight control system development and safe envelope expansion for novel eVTOL configurations.

The SWFT aircraft is a 28.6% geometrically scaled model of the RAVEN aircraft having a gross weight of 35 lb, wingspan of 5.7 ft, and proprotor diameters of 19.5 in. The SWFT aircraft has 24 independent control effectors, as will the full-scale RAVEN aircraft, and is intended to be a scaled copy of the full-scale RAVEN to the maximum extent feasible. The SWFT aircraft is largely custom designed, including custom tilt mechanisms and proprotor collective control mechanisms, with some COTS components, such as the proprotors. To facilitate compact wiring and efficient communication with many control effectors, the SWFT aircraft utilizes a Controller Area Network (CAN) bus. The CAN bus facilitates transfer of all control effector and sensor commands and statuses on a single communication bus so that data is available to both the flight controller and the data acquisition system. Development of the SWFT flight dynamics model is being supported by static and dynamic wind tunnel tests, flight-test system identification, computational aerodynamic analyses in FlightStream [21, 22] and OVERFLOW 2 [23], and in-house developed rapid aerodynamic modeling tools. Accurate flight dynamics model development supports the design of custom model-based flight control laws for the SWFT aircraft.

Development of the SWFT aircraft commenced in November 2021. SWFT was designed and built at NASA Langley with the first aircraft, SWFT-1, completed in September 2022 and an additional copy, SWFT-2, expected to be completed in summer 2023. A photograph of the SWFT-1 aircraft is presented in Fig. 9.

In February 2022, an isolated proprotor wind tunnel test was performed in the NASA Langley 12-Foot Low-Speed Tunnel (LST) to characterize proprotor performance through the transition envelope [24].

In summer 2022, NASA hired a student to utilize an eVTOL sUAS similar in size to FINCH to help develop procedures to enable rapid flight control law deployment and testing on subscale VTOL aircraft [25]. The similarities between this activity, which took place at NASA, and FINCH, at Georgia Tech, strengthened collaboration and aided problem solving.

In December 2022, a wind tunnel test of the SWFT-1 aircraft was performed in the 12-Foot LST for the bare airframe (no proprotors) and the powered airframe (proprotors installed and powered). This first tunnel entry was a static test with the vehicle orientation held constant for each test point. All 24 control effectors were independently varied and the vehicle was tested at several dynamic pressure settings in the transition flight regime, at various angles of attack and sideslip. The wind tunnel test collected data to facilitate aero-propulsive model development and to determine the transition trim envelope for tunnel dynamic pressures between 0 and 5 psf, where 0 psf corresponds to hover, and 5 psf represents a mid-transition flight condition of the SWFT aircraft. The trim flight envelope then informed design of aerodynamic characterization experiments. Technology development and lessons learned from the NASA LA-8 [26, 27] wind tunnel testing [28, 29, 30] enabled this single tunnel entry of SWFT-1 to be conducted more efficiently and collect similar data quality to that collected during all four full-airframe tunnel entries of the LA-8. Plans for continued development of SWFT include dynamic wind tunnel tests, tethered hover flight tests, and free-flight tests, including envelope expansion through the full transition corridor. Publications will follow upon completion of each key element of SWFT development, in line with the RAVEN activity's goal to enable real-time public learning throughout.[5]

Fig. 9 The SWFT-1 aircraft in the NASA Langley 12-Foot Low-Speed Tunnel, shown here with forward and tip propellers partially tilted and flaperons partially deflected.

F. Aeroacoustics Predictions and Toolchain Development

During the conceptual design phase of the RAVEN activity, a low-fidelity toolchain was developed and exercised utilizing ANOPP2 [31] to provide an initial prediction of RAVEN aircraft noise during a long-duration level flyover (one of the three rotorcraft certification points [32]). Preliminary predictions for the RAVEN aircraft during trimmed level flyover, with the vehicle directly overhead, indicated that the tonal noise dominated the unweighted overall sound pressure level, but with A-weighting applied, broadband noise was predicted to dominate, consistent with results for similar proprotor configurations [33]. This acoustics modeling exercise has helped researchers to evaluate the current best practices for predicting RAVEN aircraft noise and to understand where improvements to the toolchain are likely to be most valuable for future predictions for the RAVEN aircraft. In particular, the significance of broadband noise as part of the aircraft acoustic signature accentuates the importance of refining the accuracy of broadband prediction models because the operating conditions expected are outside of the regimes that were used to tune the Brooks, Pope, and Marcolini [34] methods widely used today. Additional research efforts to tune broadband prediction methods are underway [35].

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[5] An up-to-date list of publications is accessible from the NASA RAVEN website [36].

V. Concept of Operations

The RAVEN aircraft is envisioned to provide an enduring flight research capability with a relevant size and configuration aircraft to obtain open flight data and to advance research and technology related to AAM. In the currently proposed operating model, Georgia Tech will own, maintain, and operate the RAVEN aircraft, and NASA (and potentially other customers) will have access to the RAVEN aircraft to perform flight research and to obtain data. Georgia Tech will be responsible for ensuring air/flightworthiness, and NASA review board involvement will be dependent on the future development path of RAVEN, scope, and location of tests. NASA and Georgia Tech have compiled an initial version of a "RAVEN Concept of Operations" document which will evolve as the RAVEN activity progresses.

Selection of sites to perform testing of the RAVEN aircraft is ongoing. Different phases of the development of RAVEN, with different levels of risk, will be suited to different test sites. When determining suitability of a test site, many aspects are being considered including, proximity to Georgia Tech and available ground infrastructure at the test site. Operations of the RAVEN aircraft will progress through a number of operational scenarios as the flight envelope is expanded. It is anticipated that initial ground testing of the propulsion and avionics systems will be performed on campus at Georgia Tech. Tethered hover testing may be performed at a local site that is easily accessible to the Georgia Tech team, and untethered hover testing may be performed at a rural airport. Envelope expansion testing leading to full transition is likely to be performed at a specialized flight test site, and acoustic testing may be performed at a site selected specifically for acoustical testing.

VI. Current and Future Work

The RAVEN team is currently conducting planning for next steps in the activity. With the conceptual design closed in May 2023, the next step will be to pursue more detailed design and, ultimately, to build the RAVEN aircraft. A programmatic plan, pending funding availability, is in place that includes (1) development of a hover capable iron bird for testing and integration of the full-scale electric powertrain, avionics, and instrumentation, (2) modification of the BD-6 airframe including structural modifications, (3) design, fabrication, integration, and testing of the proprotor tilt and collective control mechanisms, (4) development of the flight control system, (5) flight test planning, and (6) ground and flight testing of the integrated RAVEN aircraft.

In support of the RAVEN activity's objective to enable real-time public learning as the RAVEN program develops, the RAVEN team endeavors to publish on all aspects of the RAVEN activity in a timely manner. Publications are intended to include technical data and lessons learned as well as organizational processes and lessons learned in the standing up of a new organization with the capability, facilities, and expertise to design, build, and test novel electric aircraft, while training next generation engineers. The NASA RAVEN website provides an up-to-date status of the activity along with all past and upcoming publications [36].

Acknowledgments

This research effort has been funded by the Transformational Tools and Technologies and Convergent Aeronautics Solutions projects within NASA's Transformative Aeronautics Concepts Program, the NASA Langley Aeronautics Research Directorate, and Georgia Tech internal funds. NASA support to Georgia Tech was provided via the National Institute of Aerospace Cooperative Agreement 80LARC17C0004, Activity NIA.COOP.05.201201. The authors gratefully acknowledge all who have contributed to the RAVEN activity to date on both the NASA and Georgia Tech teams. Patent Pending.

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