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Energy Augmentation for Vehicle Electric Systems (EAVES)

Kapil Sheth, Todd Stinchfield, Seth Schisler, Nhan Nguyen, and Corey Ippolito
Ames Research Center, Moffett Field, California

David Pike and Thomas Lavelle
Glenn Research Center, Cleveland, Ohio

Garry Qualls
Langley Research Center, Hampton, Virginia

August 2023

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Ames Research Center
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Executive Summary

This preliminary study evaluated eight concepts for augmenting the energy state of electric Vertical Take-Off and Landing vehicles. Advanced Air Mobility electric vehicles could need additional charge due to depleted batteries (e.g., strong winds along the way) while approaching their destination. There are five direct charging and three indirect charging concepts presented in this paper. The concepts are in the preliminary research stage and are being refined. Considering the concepts are for the year 2045 timeframe, there is sufficient time to evolve them, along with the designs of these electric air vehicles. This Technical Memorandum describes more detail and provides a discussion on the desirability, viability, feasibility, and wickedness of these energy augmentation concepts. A discussion of barriers and initial investigation approach for the concepts is presented as well.

One intent for the presentation of this Technical Memorandum is to capture the work done from March through September 2022 within NASA's Convergent Aeronautics Solutions (CAS) Project, in the Transformative Aeronautics Concepts Program. At the end of the effort, it was decided that only one concept would be further investigated. The rest of the concepts for energy augmentation would be described in this document and could be picked up later if NASA chose to further investigate them. This document is a collection of input from the authors regarding the concepts they worked on. It is not intended to be a conference or journal publication, but a record of research conducted on the concepts considered by the Energy Augmentation for Vehicle Electric Systems (EAVES) team consisting of the authors. Mr. Todd Stinchfield was the Principal Investigator.

Introduction

There is increasing evidence that the concept of Urban/Advanced Air Mobility (UAM/AAM) will become a reality. The electric Vertical Take-Off and Landing (eVTOL) vehicles that will transport humans and cargo are being built by many companies and many more designs are available today. NASA has developed several representative performance models that are being used for simulation purposes [1]. The Federal Aviation Administration (FAA) also has developed a concept of operations for AAM operations [2]. The research reported here followed the process of identifying current technologies and existing infrastructure to explore applicability for the energy augmentation of electric air vehicles.

Today's conventional aircraft load extra fuel as a contingency for operations in inclement weather conditions. They have flight-planned alternate airports for diversion, in case of bad weather. The eVTOLs have a maximum charge capacity when they depart that is expected to include small reserves, given the limited range of these vehicles. If there is inclement weather or strong headwinds along the way, or inability to land at the destination (e.g., disabled vehicle on the landing pad), the vehicles may need additional charge to safely land at their destination or an alternate landing Vertiport (termed like an airport, but for vertical take-off and landing vehicles). The likelihood of such occurrence is increased by the fact that the depletion rate of the batteries behaves non-linearly at lower charge levels [3]. Low-charge or emergency landing (especially under extreme weather conditions) uses even more energy and is a threat to safe AAM operations.

This Technical Memorandum explores eight concepts for directly or indirectly charging AAM electric vehicles as they get close to their destination or providing an additional boost during the departure phase from the origin vertiport, for the 2045 timeframe. First, five direct and three indirect concepts for charging are described. Then, each concept is classified in terms of the barriers that must be overcome if it is to become a desirable, viable, and feasible solution. The concepts selected for further investigation are presented along with concluding remarks.

Survey of the Current State of the Art

Electric air vehicles for human and heavy cargo transport are being designed and developed, and a few production models are attempting to secure FAA certification. For smaller drones carrying a payload of 50 lbs or less, the flight range is short, and the costs associated with energy augmentation mechanisms may not be justified. The study reported here is a first-of-its-kind for energy augmentation for larger electric UAM vehicles. Some of the technologies for charging ground vehicles have analogs that may be suitable for airborne vehicles (e.g., charging platforms, analogous to charging stations for ground transport), but they do not exist yet for larger electric air vehicles, carrying more than payloads of 55 lbs.

Current literature suggests that fully electric air vehicles are not practical for carrying humans and cargo for more than 100 nautical miles [4, 5]. Transportation concepts involving electric air vehicles often are limited to hybrid powertrains, since even optimistic battery models do not have sufficient energy density for flight of more than 250 miles. Therefore, creative solutions for electrical energy augmentation are needed to help increase the viability of fully electric air vehicles.

Focus Area and Assumptions for Energy Augmentation

The technologies considered in this study were limited to the arrival and departure phases of an AAM flight. The enroute phase was not considered for energy augmentation because the motivation for this study came from two aspects: 1) Dealing with drawing of high current during the depleted state of a battery, and 2) Handling safety and emergency situations and battery malfunctions during the high-battery-drain phases of arrival and departure.

Thermal management of batteries is an important consideration when drawing high current during recharging; however, this study does not address those considerations. It was also assumed that vehicle designs will be modified over the next many years to accommodate the implementation of the futuristic concepts presented here.

Concepts for Direct and Indirect Charging

The current work evaluates five Direct Charging and three Indirect Charging concepts. The following two sections detail the concepts considered. These concepts were conceived by the NASA research team based on literature review and currently available mechanisms/processes.

Direct Charging Concepts

Direct Charging involves a physical connection between the charging equipment and the eVTOL vehicle. The five direct charging concepts considered for this study are:

1) Charging Platforms,
2) Swappable Batteries,
3) Flying Batteries,
4) Cable Power, and
5) Hybrid.

Charging Platforms

Charging Platforms are like gas stations for internal-combustion engines or charging stations for electric vehicles along streets or freeway exits. They are envisioned as tall structures (somewhere between 400-600 ft) within the vicinity of the vertiports (perhaps a mile or two away). The vehicles can land, recharge to whatever level of need, and continue to the destination. Based on current thinking, it appears that AAM vertiports will be at ground level (large dirt patches), higher at about 50-60 ft (tops of parking garages), or even higher at 200-300 ft (tops of skyscraper buildings), etc. Landing at an elevated charging platform from a cruise altitude of 4000 ft (based on current AAM concepts of operation [1]) would require less energy than a lower alternative. Such elevated charging platforms could be scattered across the cities or rural landscapes where AAM vehicles could recharge to extend their flight range [6].

Charging platforms could also be placed strategically to accommodate arrivals and departures from various vertiports, accounting for their direction of flight. There is a one-time expense to build the platform, and then the rest of the cost is in generic, regular maintenance. Figure 1 (left) shows a picture of the space needle in Seattle, WA. Figure 1 (right) shows a stick-representation of the structure. The Space Needle is representative of size and shape of a charging platform. The top would be flat for a charging platform (disk-like with a fence for safety), where the vehicles would land, and a charging port (represented by the triangle on top) would be available to plug in. Depending on the size of the platform, this process could be performed by a human or a telescopic charging arm from the platform or from the vehicle (like the cargo capsule attaching to the International Space Station).

Figure 1: A potential charging platform sample like the Space Needle (Seattle, WA, height 605 ft).

Advantages

A single charging platform could service either one or multiple vertiports based on vertiport density. Charging platforms are stable and can deliver the required power. Additionally, since the charging platforms are located high above street level, they will be more physically secure. Finally, charging platforms offer a long-lasting solution that could operate in almost all-weather capability and could function as alternate vertiports.

Disadvantages

Charging platforms will have a high initial cost due to their infrastructure. Vehicles must dock (either land and plug-in or charge by induction) to the tall structure in order to charge, and wind conditions at that altitude could be more hazardous than at ground level. Similar to a vertiport, the charging platforms will require coordination by air traffic controllers.

Swappable Batteries

Swappable Batteries is a concept where the vehicles could carry a spare battery as a contingency. It is somewhat analogous to the 2-gallon gas can that some people carry in their cars. That could be a tradeoff between extra person (payload) on-board vs extra range, depending on operating conditions that day. This concept would require modification to the basic design of the vehicle. The AAM vehicle design would need to be amended for the extra slot for multiple swappable batteries which could be standardized or specific to the design of that vehicle. This concept does not impact the primary battery charging system because it is for augmentation purposes. Figure 2 shows one way to carry the spare batteries hidden between the passenger seats in an insulated container. One disadvantage of this concept is that, unlike conventional aircraft, the weight of fuel (battery) does not decrease as it is consumed. Also, the required extension to flight time (and range) would need to be estimated before takeoff, to carry the necessary additional batteries on board. That implies that if they are not utilized, dead weight was carried during that origin-destination journey.

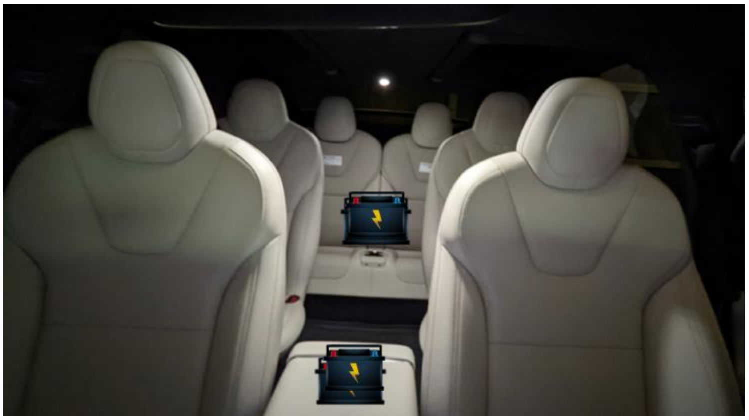

Figure 2: A potential design to embed the spare and swappable batteries in the cabin.

Advantages

Swappable batteries will provide extra power for any phase of flight. Depending on the range required and estimated potential excess flight time due to strong winds/weather, the relevant number of batteries could be carried.

Disadvantages

Battery energy densities need to be much higher (with smaller size) for additional batteries to be carried. Extra batteries, if unused, are excess weight that will offset passenger capacity.

Flying Batteries

Due to the dead weight aspect of swappable batteries, flying batteries are considered. This energy augmentation concept evolved from the notional concept of airborne platforms that could charge eVTOL vehicles, similar to charging platforms on the ground (see Figure 3 above). Floating platforms (like balloons and blimps) are expensive to build and difficult to maintain. The flying batteries would have rotors attached to them, which would carry them to the AAM vehicle, with internal control and automation. The battery would “fly” to the vehicle and dock on or under it (depending on design of the AAM vehicle) during hover or cruise. Once the charging is complete, the battery would undock and fly back to a docking location on the vertiport or the nearby charging platform, from where it originated. This process is described in [7] for small drones. A demonstration of that technology is available [8]. The weight of the battery is an important consideration, and research is being conducted to assess the power requirements for the rotors. Also, the autonomous control system needed to guide the flying battery through unsteady wind patterns could be an issue. Figure 3 shows a cartoon battery with a rotor on top (left) and an AAM vehicle with the docked battery at the bottom (right).

Figure 3: A battery with rotor(s) (left) and a battery docked to an AAM vehicle (right).

Advantages

The supplemental battery pack provides extra power for takeoff. If necessary, additional batteries can be delivered to support power requirements. Augmented battery weight does not need to be carried for entire flight.

Disadvantages

A battery docking bay onboard the AAM vehicle is necessary. The Guidance, Navigation and Control (GNC) system for flying batteries needs reserve power for its own control systems. There's also a potential safety risk if the battery does not successfully dock on the vehicle. The flying battery GNC can be complex and will require certification.

Cable Power

Cable Power is a concept developed to address weight issues associated with a flying battery. One could potentially consider a charging cable or tether utilizing a winch to be flown to an eVTOL, using a drone (powered by the cable). The drone is like a tugboat guiding a bigger ship with ropes. The limitations of this concept are the length and weight of the cable, along with the sway of the cable during unsteady winds, the docking and undocking, and retraction of the heavy cable. Figure 4 (below) represents a winch, cable, and a tug-drone approaching an AAM vehicle.

Figure 4: A power cable being flown to charge an AAM vehicle.

Advantages

Cable power offers high power efficiency and stable power quality. The system would likely require no additional onboard power management and distribution, so it would likely add no mass to the flight vehicle. Cable power could offer other features like active thermal management.

Disadvantages

Cable power is limited in range. The cable weight (1 kg/m) limits takeoff power augmentation effectiveness since the weight will significantly limit how much cable can be used and, in turn, how much power could be delivered during the takeoff and landing phases. Additionally, vehicle docking mid-air might be prohibitively difficult in adverse weather, which is when augmentation might be needed the most. Adverse weather conditions might also make the cable impossible to safely raise, and a failure of the cable or control drone could create a serious hazard for people and equipment in the area. The airspace to effectively manage the separation between power cables and proximate vehicles would be complicated and potentially hazardous.

Hybrid

Hybrid concept is a combination of the charging platform, swappable batteries, flying batteries, and cable power. It is expensive to build the charging platform higher than about 400-600 ft. The flying batteries are limited by the weight of the battery. The cable power has weight and retraction mechanism concerns. The thought for the hybrid concept is to be able to combine all four concepts into one, such that the limitations can be reduced to more manageable levels, and yet be able to provide energy augmentation at a high enough altitude to the AAM vehicle. Figure 5 depicts the hybrid concept with the previous four concepts simultaneously.

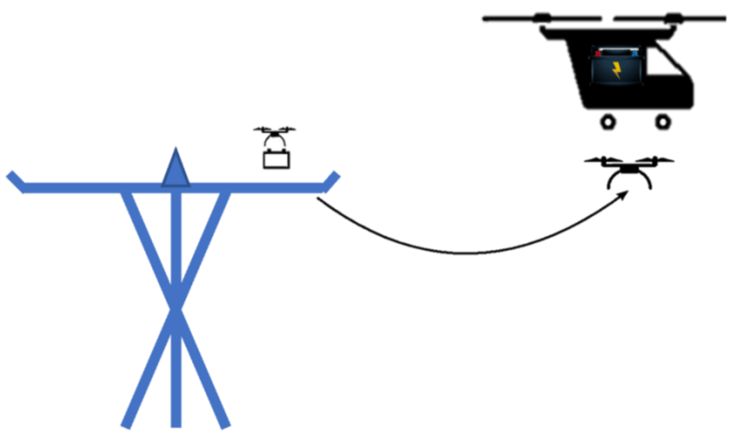

Figure 5: A power cable being flown to charge an AAM vehicle.

Advantages

Delivers high power transfer efficiency and could offer other features like active thermal management. The tower would partially support the cable weight allowing for additional length. The tower keeps battery and AAM vehicle traffic separated by altitude.

Disadvantages

Cable weight (1 kg/m) still limits takeoff power augmentation effectiveness. The airspace to effectively manage the separation between power cables and vehicles would be complicated and potentially less efficient.

Indirect Charging Concepts

Indirect Charging or “power beaming” refers to the concepts that do not involve any physical contact (e.g., wireless) between the charging equipment and the AAM vehicle. The three modalities for Radio Frequency (RF) power-beaming concepts being considered are:

1) Optical/Infrared,
2) Millimeter Wave, and
3) Microwave.

Optical/Infrared power beaming

This concept uses lasers within the infrared (IR) spectrum for indirect charging. Such a mechanism would be used for longer-range charging with advantages in terms of the geometric transmit and receive aperture sizes. This is especially true for AAM vehicles, where space is limited, and a small area footprint is desired. The Optical/IR charging would involve wireless energy transfer from a beam generated by a fiber-based laser input source and received by a modified photovoltaic (PV) cell receiver on the electric aircraft for end power conversion. Such a system would also need a modification on the AAM vehicle to embed an active thermal management system on the reverse side of the modified PV cell to dissipate excess heat received.

Millimeter (mm) wave power beaming

This concept uses directed propagating millimeter waves for indirect charging. Such a mechanism would share a similar small footprint compared to optical power beaming but primarily used for shorter-range charging, since the area of the sensor required for longer range would be prohibitive. Remote charging would involve wireless energy transfer through a millimeter transmitter to a phased array rectenna (rectifying antenna) for RF-to-DC power conversion. Such a system would also need a modification to embed an active heat exchanger on the AAM vehicle to dissipate excess heat.

Microwave (MW) power beaming

This concept uses directed propagating microwaves for indirect charging. In contrast to optical and millimeter wave charging, microwave power beaming is well-suited for high power, all-weather and long-distance applications. (See Table 1 and Microwave Power Beam Indirect Charging Section for more details.) It is also better understood for scaling up size and power. Remote charging would involve wireless energy transfer through a microwave transmitter to a phased array rectenna for RF-to-DC power conversion. Such a system would also need a modification on the AAM vehicle to embed an active heat exchanger on vehicle to dissipate excess heat.

Advantages and Disadvantages

Figure 6 (below) displays the mechanism for charging an AAM vehicle with any of the indirect charging RF power beaming mechanisms mentioned above. The three types of power beaming modalities within the RF spectrum (laser, millimeter wave and microwave) were evaluated to determine which concept is least feasible. At the operational distances anticipated for energy augmentation at a vertiport, MW power beaming has up-front advantages. MW power beaming is viable in all weather, was demonstrated in 2022 [9] to be safer, and has higher

Figure 6: An AAM vehicle being charged by RF power beaming process.

power efficiency with better technology heritage developed. While laser power beaming has advantages in terms of geometrical transmit and receive aperture sizes for situations where there is limited area or a small footprint is desired, it performs poorly in foggy conditions and may not be usable in certain environments or situations. The results from recent Wireless Power Transmission (WPT) research completed independently by the Naval Research Laboratory (NRL) and Defense Advanced Research Projects Agency (DARPA), respectively, favor the delivery of energy over microwave (MW), 300 MHz (λ = 1 m) up to 300 GHz (λ = 1 mm), wavelength band within the RF spectrum [10]. Thus, overall, MW is a better choice for static flight operations in the power beaming (shorter) distances of relevance to AAM, and laser power beaming is better suited for dynamic flight operations at longer distances, as shown in Table 1 [10].

Table 1: Comparison of power beaming modalities (red implies poorer performance).

	Optical	Millimeter Wave	Microwave
Penetration clouds/rain/fog	No	Poor	Excellent
Conversion Efficiency Performance limits for DC-to-RF&RF-to-DC conversion	OK	OK	Good
Required Aperture Size Transmit and receive antenna sizes	Small	Medium	Large
Safety Personnel exposure limits, beam containment, user perception	OK	Good	Good
Economy of Scale Based on present state of the art to deliver thousands of kW over thousands of km	Poor	Poor	Good

Rejected Concepts

Some of the energy augmentation concepts that were brought forward initially were determined to be less feasible and were rejected due to the identification of the more plausible approaches described above.

Floating Platforms/Aerial Recharging

This concept refers to the construction of airborne platforms (e.g., airships) that would be equipped for AAM vehicle docking and recharging. The floating platforms would be placed in both the enroute structure and near vertiports to act similarly to charging stations on the ground for EVs. The largest barrier identified for this concept was the construction and operational cost of the platforms.

Magnetic Induction

Magnetic induction was considered as an indirect charging method to be used at vertiports. This method is highly desirable for charging AAM vehicles while they are parked. Magnetic induction is limited in range so drastically (only a few meters) that a cable is more efficient. Additionally, magnetic induction would require a massive inductor, which logistically would be difficult. The practical distance for charging with magnetic induction was not suitable for the desired charging operating environment out to 1 km.

5G/xG Wireless Charging

Wireless charging through 5G transmissions (mm-wave) was considered as another indirect charging concept to be used at vertiports. Unfortunately, there exist large feasibility barriers associated with the amount of power that could be transferred. Currently, only microWatts of power can be transmitted and collected with this method, and future power scalability is uncertain within the time horizon of this study.

Barriers Addressed for Classification of Concepts

Desirability (interest from invested parties or stakeholders and public), Viability (economic practicality), and Feasibility (technological plausibility) of the energy augmentation concepts were assessed to further classify them and select for additional consideration.

The desirability of a concept addresses how well the concept would serve the needs of AAM stakeholders and the general public. Would it be better to have such an energy augmentation concept, or is an alternate approach more suitable? The public perception of such concepts is an important aspect to address with the desirability consideration.

Viability considers the monetary cost of the concept implementation. This includes the initial cost (e.g., the cost of building the charging platform), the operational cost (e.g., maintaining the winch for cable power and maintaining the battery capacity for a flying battery), maintenance cost, recycling cost, etc.

Feasibility is related to the technical plausibility of the concept and whether it can be achieved (e.g., charging indirectly with a laser, while maintaining the safety of the charging vehicle, the passengers onboard, and other vehicles/people/property in the vicinity).

Within NASA, consideration is also given to the difficulty and creativity, or as suggested, “wickedness” of the new concept. The wickedness addresses the multiple, interdependent, dynamic, and uncertain aspects of the concepts.

Some of the barriers that need to be considered across all the proposed concepts for desirability (D), viability (V), feasibility (F), and wickedness (W) (see Figure 7 below) are:

- (F) Power management system,
- (F/W) Rendezvous flight autonomy,
- (F) Thermal management during charging,
- (V) Lifecycle costs (operations and maintenance),

- (F) End-to-end efficiency,
- (D) Additional noise,
- (D) Public perception,
- (V/F/W) Airspace complexity,
- (F) Additional vehicle weight and drag.

Figure 7 (below) illustrates the process that was utilized to generate a set of execution events. Our team started with an evaluation of barriers that exist for each of the potential energy augmentation concepts. Next, we compared barriers for each of the energy augmentation methods to build a list of barriers that were present for more than one method; we call these shared barriers. To maximize the impact of our research, the execution events were designed to reduce or remove the shared barriers, thereby enabling the research to positively impact more than one energy augmentation concept.

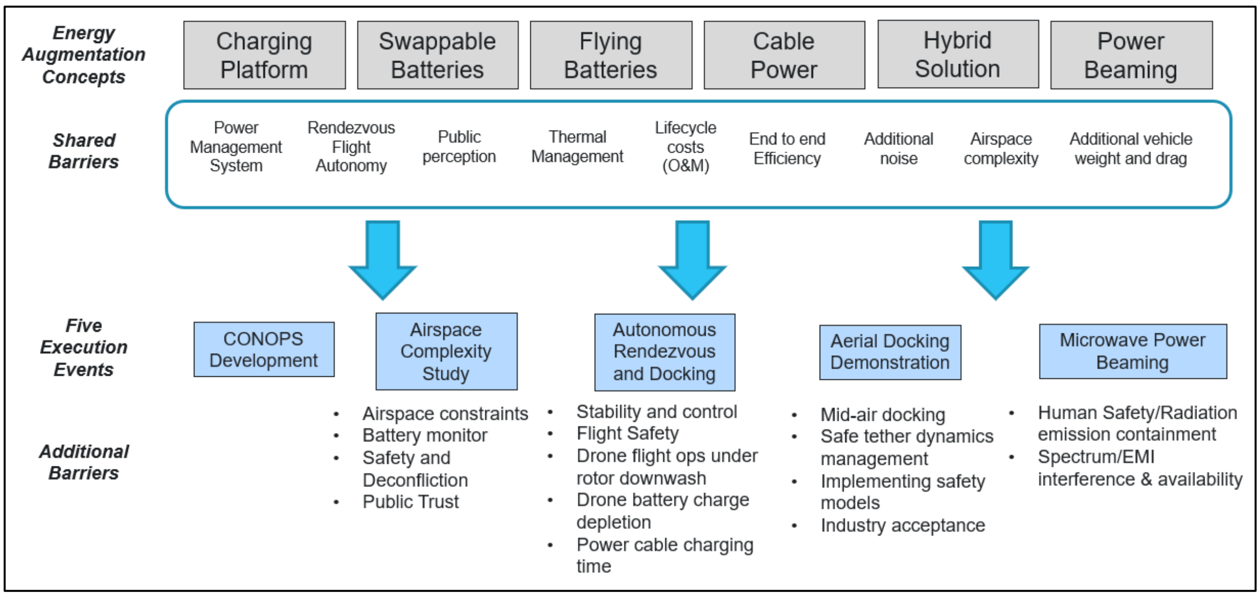

Figure 7: Execution event selection method based on shared barriers of six energy augmentation concepts.

Proposed Activities for Investigation

To mature energy augmentation concepts for AAM, a multi-prong approach is taken to address both direct and indirect charging concepts, considering the above-mentioned barriers. Technology development includes technology flight demonstrations, simulations of full-scale systems, and system analysis. The potential areas of technology development for AAM energy augmentation could include but are not limited to the following:

- Simulation-based study of the local vertiport and regional airspace for airspace complexity of operations [11, 12],
- Rendezvous of two autonomous small-scale eVTOL vehicles in operationally representative environment [13, 14],
- Drone and vehicle flight dynamics and control in operationally representative environment [15, 16],
- Flying battery quick connect/disconnect for docking and undocking from AAM vehicle,
- Power cable in-flight docking and vehicle dynamics in operationally representative environment, and
- Safety/efficiency study for RF (specifically microwave) power beaming to an AAM vehicle.

The first research activity that is envisioned to start this research effort is the development of the Concept of Operations. The ConOps document defines the set of operationally representative conditions that will be incorporated into test and demonstration planning for the energy augmentation concepts under consideration. The ConOps document also determines which energy augmentation concepts show the potential for increased operational efficiency at vertiports. Once that document is developed, the following four research activities are expected to proceed for further investigation:

A. A study of energy augmentation methods and airspace complexity,
B. An investigation into autonomous rendezvous and aerial docking,
C. An aerial docking demonstration, and
D. A safety evaluation of energy augmentation power beaming.

These research activities are being considered for further investigation according to the barriers they address. Also, they address likelihood of success of the concepts in the twenty-year timeframe and were most relevant to the problem at hand. A brief description of each activity is presented in the following sections.

Study of Energy Augmentation Methods and Airspace Complexity

1. Purpose

This activity will provide an assessment of the complexity of airspace from an air traffic manager's perspective when various energy augmentation methods are implemented. (Note: for this section, the words method and activity are used interchangeably.) When the density of traffic increases (e.g., with flying battery autonomous flight), the airspace complexity and the air traffic manager's workload could significantly increase. This activity provides an estimate of complexity under various traffic scenarios by including different vehicle types (operating envelopes) and various constraints (operating environments, e.g., constrained airspace due to power beaming, increased noise, and low battery charge). Today, conventional air traffic operations are delayed when the airspace complexity exceeds certain thresholds (e.g., number of aircraft in a specific region). The study will compute the level of airspace complexity based on the proposed scenarios and evaluate the feasibility of implementing energy augmentation operations. The analysis of additional time taken for energy augmentation and the associated cost of operations, is envisioned to be a part of this study.

2. Method Approach

This Study of Energy Augmentation Methods and Airspace Complexity (SEAMAC) will initially focus on activities toward developing a simulation platform/environment of AAM vehicle operations [11, 12] for each energy augmentation method that will be supported by the other three (autonomous rendezvous, in-flight docking, and power beaming) activities. Each scenario will include the following:

1. Description of the operating environment and the dynamic scenario with constraints (F/W)
2. Definition of the performance characteristics of the AAM vehicle(s) (F)
3. Definition of the physical characteristics of the energy augmentation system (V/F/W)
4. Evaluation of the complexity of the defined scenario (F/W)
5. Assessment of benefits and limitations (V)
6. List of assumptions, stakeholders, and recommendations (V/F)

3. Barrier(s)

SEAMAC primarily addresses the barrier of Airspace Complexity. At the vertiport, Airspace Complexity (V/F/W), limits the feasibility and efficiency (viability) of energy augmentation methods at currently planned and futuristic air traffic densities. Detailing the complexity of airspace for each energy augmentation method will assess the feasibility of efficiently moving traffic through AAM airspace, particularly in the vicinity of vertiports during energy augmentation operations. This assessment enhances the safety and regulatory compliance for the energy augmentation methods. The mechanisms for addressing constrained airspace around augmentation operations are part of the scenario description. The modeling of eVTOL vehicles along with autonomous rendezvous vehicles and the mechanics of flying battery docking are dynamic and uncertain (W). The modeling in the simulation platform will address these.

4. Criteria

Three criteria will be used to determine the effectiveness of study for energy augmentation methods for airspace complexity (D). 1) study will recommend effective and low-complexity energy augmentation operations to positively influence public opinion and provide a safety assessment from the air traffic manager's perspective (V). The SEAMAC activity will inform efficient operations at vertiports for different vehicle models in the presence of winds with low noise and preliminary monitoring of battery health. 2) This study will help improve the market for eVTOL vehicles (from a safety and throughput analysis) and is critical to ensure airspace access for flight operators and the Federal Aviation Administration (FAA) (F). 3) This study will support and rate activities for AAM energy augmentation, while considering varying levels of traffic densities and schedules. Such work has been undertaken for conventional traffic and a preliminary framework exists as shown in Figure 8. Several AAM vehicles (in black and yellow) are shown flying on direct routes between origin/destination pairs, along with noise contours and battery-left percentages (shown in red). Such an assessment for AAM has not been performed before and would be a first of its kind to address the complexity of airspace for traffic manager/flight operator and public acceptance. The elements required for this study (models of vehicles, battery health monitoring, noise footprints, etc. [12]) are being developed independently and will be integrated in this effort (W).

5. Anticipated Outcome

The study of energy augmentation methods and airspace complexity will be used primarily for internal recommendations and assessment. However, the scenarios and complexity parameters may be released externally through technical publication(s). For NASA, the study will prescribe future direction for energy augmentation method development.

6. Stakeholder(s)

The stakeholders that are primarily supported through the SEAMAC activity are vertiport operators (D), Airlines and AAM Operators (V), and FAA and NASA (F). The SEAMAC supports vertiport operators and FAA/AAM personnel by providing an assessment of energy augmentation methods that will improve safety and efficiency of the AAM eVTOL operations. The study responds to NASA requirements by refining the set of operationally representative conditions for test and demonstration planning for the other direct and indirect energy augmentation activities.

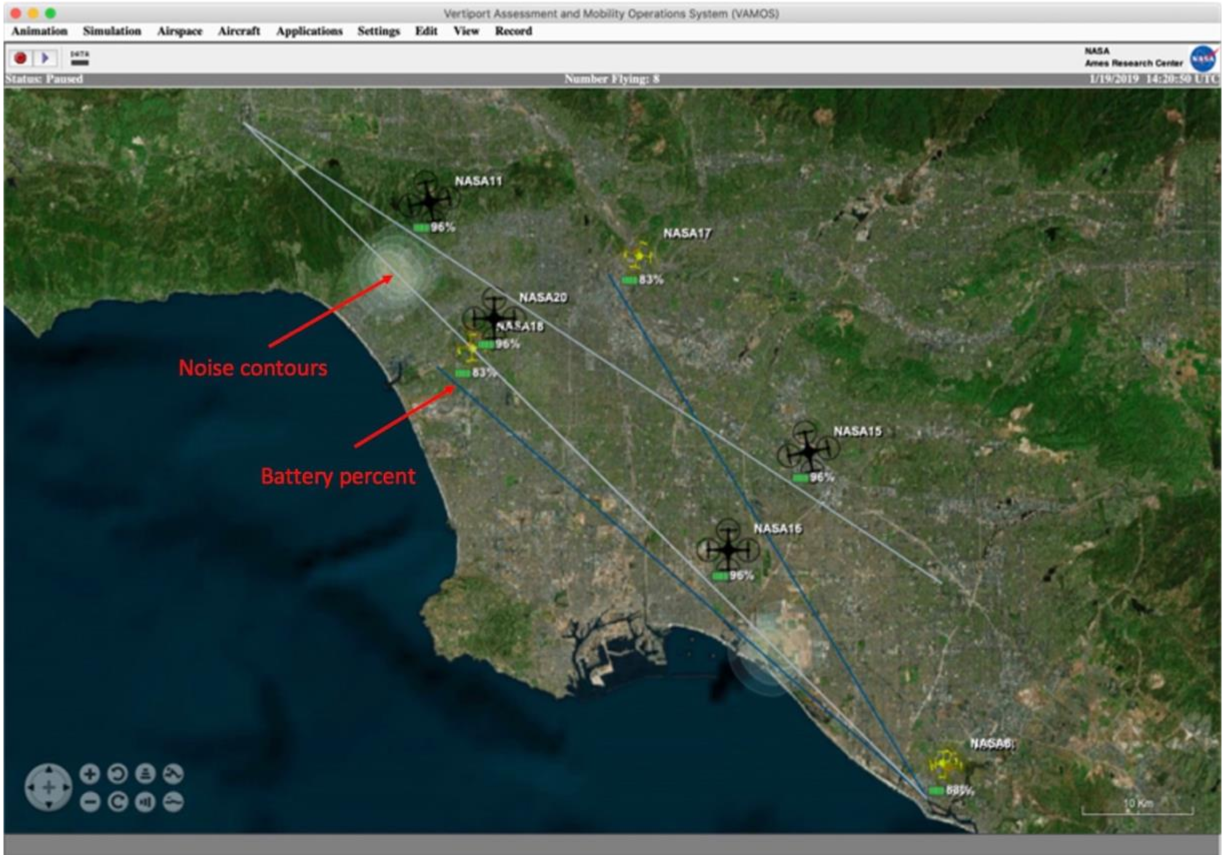

Figure 8: Preliminary design sketch for the SEAMAC activity, with noise contours and battery display.

Autonomous Rendezvous and Aerial Docking

1. Purpose

This research activity will identify and conduct development of autonomous rendezvous technology to reduce barrier risks for AAM energy augmentation concepts. The purpose of the autonomous rendezvous is to develop capabilities to safely deliver via drones to AAM vehicles the energy augmentation sources which could be either batteries or power cables in an energy-efficient manner.

Flying battery concepts for AAM energy augmentation can provide direct solutions for UAM vehicles to augment the power requirement during takeoff and landing phases or energy requirement for continued cruise. Autonomous Rendezvous and Aerial Docking (ARAD) is an enabling capability for this direct energy augmentation concept. One possible flying battery concept is illustrated in Figure 9 showing a NASA Lift+Cruise UAM vehicle [13] in rendezvous and docking with a drone delivering a battery. This concept of operation may involve a process that is composed of various approaches, some of which are identified as follows:

- Request for energy augmentation by UAM vehicle operating in the vicinity of a vertiport during takeoff, en-route, or landing
- UAM vehicle transitioning to hover awaiting battery delivery
- Battery delivery drone deployment from vertiport to perform autonomous rendezvous and docking with UAM vehicle
- Battery attachment to empty battery bay via quick connect actuation mechanism
- Drone undocking from battery

- UAM vehicle performing power management to connect replacement battery to and disconnect depleted onboard battery from aircraft electrical system
- Drone performing docking and making connection to depleted battery
- Depleted battery detached from battery bay via quick disconnect actuation mechanism
- Drone performing autonomous flight back to vertiport

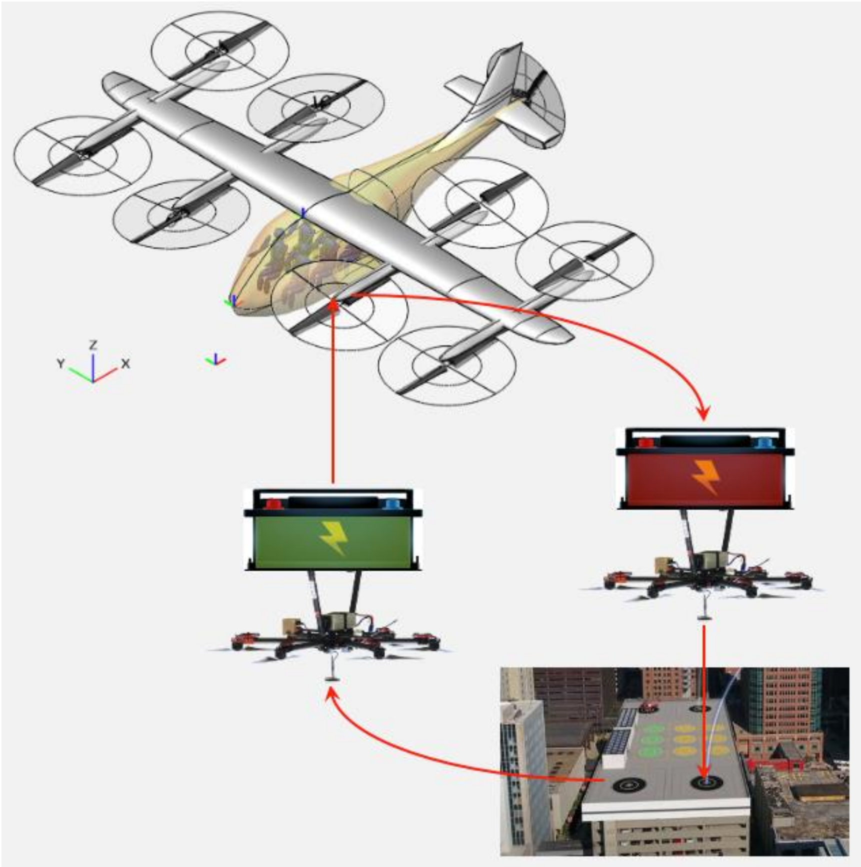

Figure 9: Flying Battery Concept of Operation.

Direct charging with power cable is also a possibility. A concept of operation involving power cable may be akin to in-flight aerial refueling as illustrated in Figure 10. The power cable provides the direct charging via a probe-and-drogue concept. A hovering UAM vehicle deploys a power cable with a drogue at the end to receive the power cable attached to a drone. The probe end of the power cable is controlled via a robotic arm to align the probe with the drogue. The drone and the robotic arm actively control the position and orientation of the probe to maintain connection with the drogue during charging.

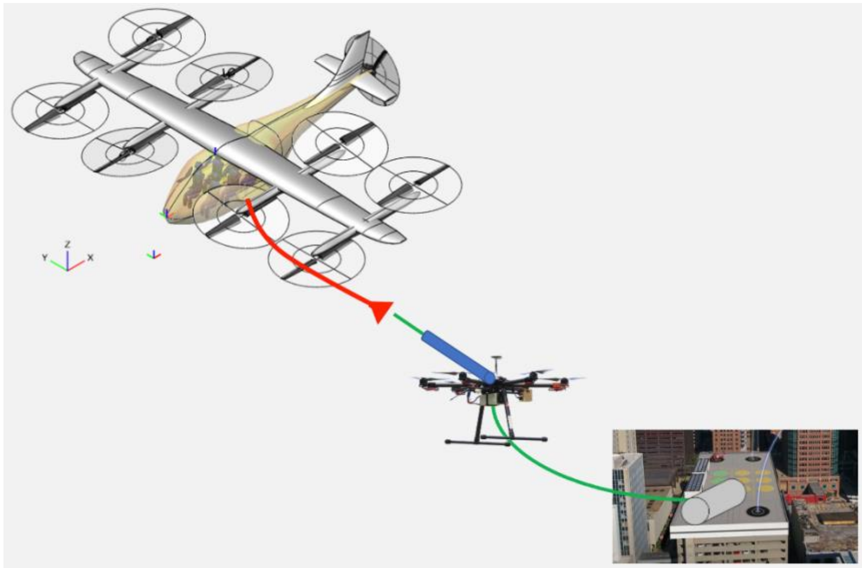

Figure 10: Power Cable Concept of Operation.

In both concepts of operation for the flying battery and power cable, the ARAD is considered a shared capability. This autonomous capability may include sensor-directed guidance and navigation via GPS or vision-based sensors [14]. Inner-loop flight control is an integral part of the rendezvous flight autonomy to maintain the guidance trajectory under a highly dynamic environment due to the rotor downwash as well as turbulence and wind gust. Autonomous sense-and-avoid capability may be required for collision avoidance between the UAM vehicle and the drone during proximity operation. Precision positioning control tasks are necessary to enable the battery and power cable to make connection to the receiving targets. Trajectory optimization may be considered necessary to develop guidance laws that can minimize the battery charge expenditure by the drone.

2. Method Approach

To develop the ARAD capability, a research roadmap was developed as shown in Figure 9 to include the following research elements:

- System analysis
- Vehicle dynamic modeling
- Autonomous Rendezvous and Aerial Docking (ARAD) system development
- Subscale flight demonstration

Each of the work elements is further defined in the subsequent sections.

1) System Analysis

The system analysis studies will identify preferred energy augmentation concepts for flight autonomy development. A limited number of potential concepts will be studied for both the flying battery and power cable. The task plan to be performed under the system analysis work element will include, but are not limited to, the following:

- The AAM vehicle definition is tentatively the reference Lift+Cruise vehicle developed by the NASA Revolutionary Vertical Lift Technology (RVLT) project as shown in Figure 12. Other AAM vehicle concepts may be considered if schedule and resources permit.

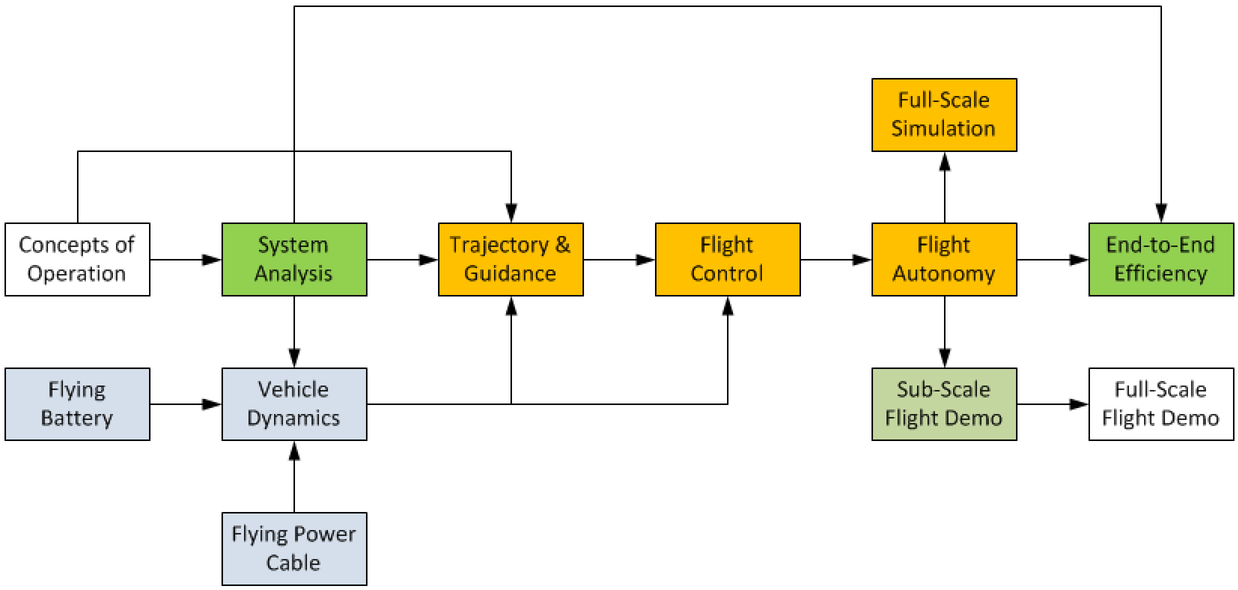

Figure 11: Research Roadmap for Autonomous Rendezvous Development for Direct AAM Energy Augmentation.

- The AAM vehicle performance and energy requirements will be obtained from existing RVLT published data or created by vehicle modeling tools, such as Comprehensive Hierarchical Aeromechanics Rotorcraft Model (CHARM) [15] and Open Vehicle Sketch Pad (OpenVSP) [16]. The performance parameters include vehicle weight, rotor power, on–board battery weight, and power requirements for hover operations.
- Weight, power, and energy requirements for flying battery and power cable will be estimated.
- Drone sizing for flying battery and power cable and performance model will be developed.
- The impact of the flying battery/power cable-carrying drone system during docking on the performance of the AAM vehicle (lift, drag, and pitching moment, rotor thrust and power) will be assessed.
- End-to-end efficiency studies will be conducted to compare total energy expenditure of AAM vehicle and energy augmentation methods.

2) Vehicle System Dynamic Modeling

Flight dynamics and control of both the UAM vehicle and drone are an important consideration for ARAD. The motion of an aircraft in wing wakes and rotor downwash can be complex to control [15]. The stability of the drone carrying the battery or power cable could potentially become degraded, potentially making flight control and rendezvous-docking tasks particularly challenging. When docking, the coupled UAM vehicle-drone system could have different dynamic characteristics if the total weight of the drone and battery constitutes a significant percentage of the UAM vehicle gross weight. The changing gross weight could adversely affect the dynamic modes of the UAM vehicle, which in turn could compromise the pilot handling and passenger ride qualities. Thus, special consideration in flight control system design may be necessary to restore or improve the handling and ride qualities [16].

The power cable concept brings its own unique set of technical challenges in terms of rendezvous flight autonomy and control. The UAM vehicle, drone, power cable, and the cable winch form a coupled system. As the power cable is extended in length, the cable tension can vary greatly due to the variable dynamics of the power cable. The tension can be influenced by the loading generated by the atmospheric turbulence, cross winds, and rotor down wash as illustrated in Figure 12. The tension in turn generates forces and moments acting on the drone as well as the UAM vehicle when the cable probe is attached to the drogue. Active tension control methods, therefore, are necessary to manage the power cable tension. Control systems to manage power cable tension could be developed as a dedicated actuator system housed within the cable winch as well as an integral part of the flight control systems on the drone and the UAM vehicle which need to be able to maintain controlled altitude and orientation. The dynamics of the power cable can be difficult to ascertain due to the variable cable length and the aerodynamic loading acting on it under atmospheric turbulence, cross wind, and downwash. Therefore, the ability to control the power cable during a rendezvous-docking maneuver may be a technical barrier.

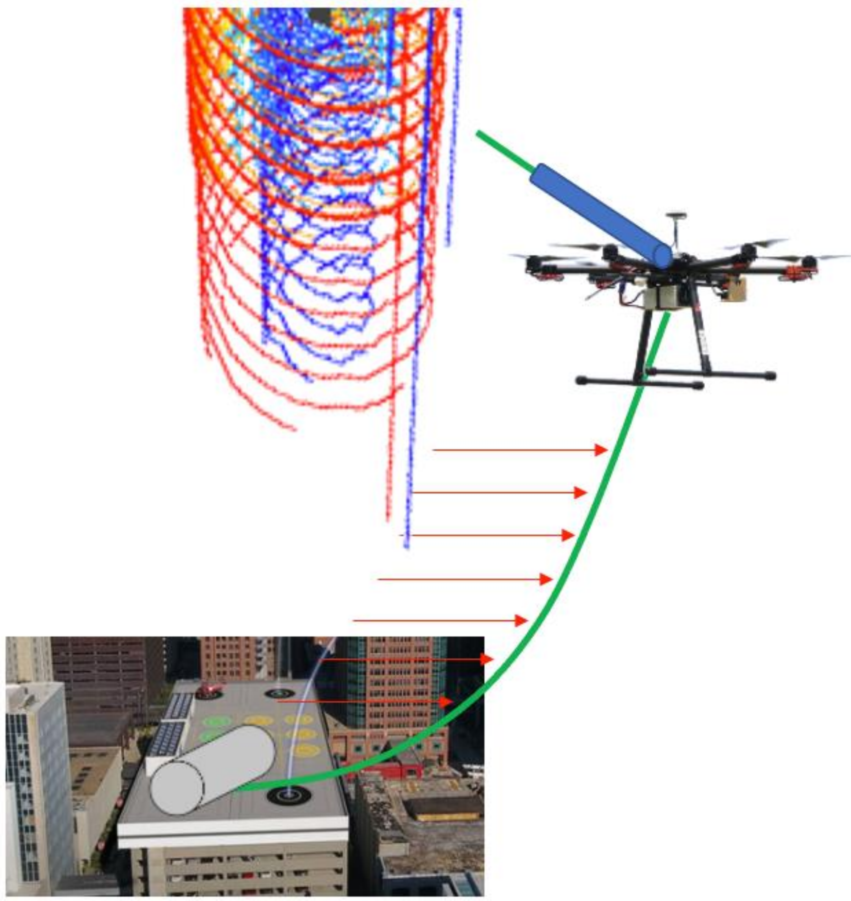

Figure 12: Power Cable in Cross Wind and Rotor Downwash.

To assess the viability and feasibility of the energy augmentation concepts and support the ARAD capability development, vehicle system dynamic models will be developed. It will be assumed that the AAM vehicle will be in hover or transition flight for the flying battery concept, but the flying power cable concept will require the AAM vehicle to be in hover. The task plan for this work element will include, but are not limited, to the following:

- 6-dof flight dynamic models of the AAM vehicle and flying battery/power cable-carrying drone will be developed. The models will incorporate coupled effects which include rotor downwash on the drone, added mass of the drone on the AAM vehicle, and forces and moments generated by the power cable on the AAM vehicle.
- A dynamic model of power cable sway under tension and aerodynamic loading due to cross wind, turbulence, and rotor downwash will be developed.

- Rotor downwash in hover and forward flight will be modeled using vehicle modeling tools, such as CHARM as shown in Figure 13.
- Stability and control assessment for the coupled AAM vehicle-drone system will be performed.

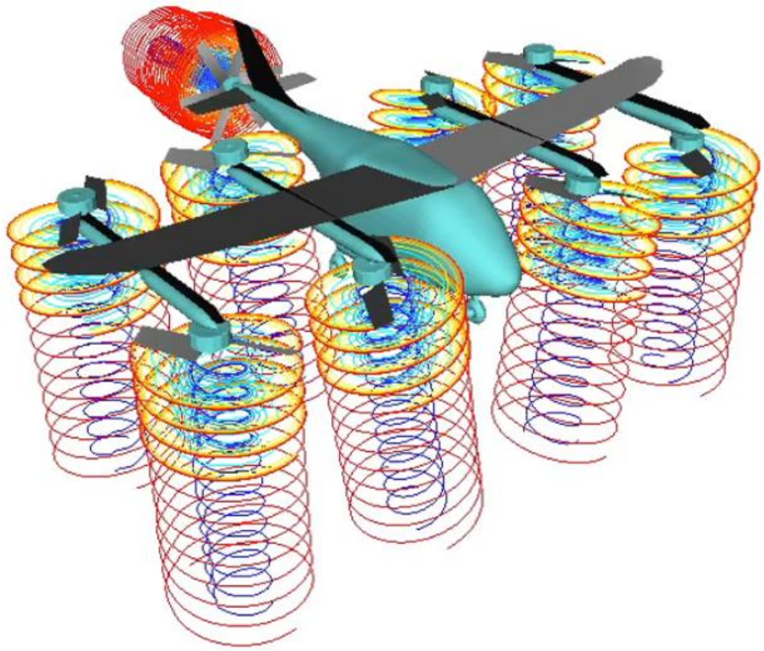

Figure 13: Downwash Model of Lift+Cruise Vehicle in Hover Computed by CHARM.

3) Autonomous Rendezvous and Docking (ARAD) System Development

The ARAD system will be developed to enable safe, autonomous guidance, navigation, and control (GNC) of the AAM vehicle and the drone carrying the flying battery or power cable. The scope of the ARAD system will include development of capabilities for the drone to perform the autonomous rendezvous maneuvers from the vertiport to a rendezvous point but will not include development of capabilities to perform the physical docking of the drone or the physical connection of the battery or power cable to the AAM vehicle. A conceptual first-level systems architecture decomposition of the ARAD system architecture for a flying battery/power cable drone is presented in Figure 14.

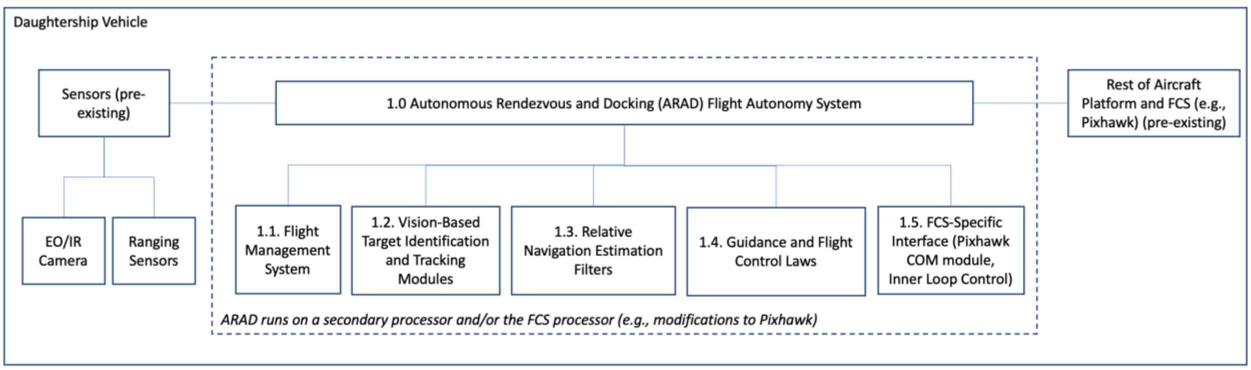

Figure 14: ARAD System Decomposition.

The ARAD system development will include the following functional decomposition:

• Flight management systems (FMS)

A candidate implementation of the FMS which provides coordination between the various ARAD subsystems for executing the rendezvous and docking maneuvers will be developed.

• Vision-based target identification and tracking module

The target identification and tracking module is responsible for acquiring the coarse-mode and fine-mode targets supporting relative-navigation requirements for safe precision maneuvering. The specific algorithms utilized for detection and tracking will be selected based on the design of the fine-mode and coarse-mode markings developed for the docking apparatus as part of the flight test infrastructure development task. Candidate techniques will be identified through a literature survey and by leveraging distributed sensing work under the NASA Transformational Tools and Technologies (TTT) project.

• Relative Navigation Estimation

The responsibility of the relative navigation estimation module is to produce precise GPS-free relative state estimation from the output of the target tracking module and the aircraft standard onboard navigation sensors. This module will develop optimal filters that combine inertial measurement units (IMU), magnetometers, and airspeed data sensor measurements. A representative vision-based estimation system for precision navigation of the drone will be developed by utilizing an extended Kalman filter (EKF) to filter IMU and vision-based image-processing targets.

This module is also responsible for planning the optimal guidance trajectories. The initial implementation will be a precomputed optimal trajectory. An online real-time trajectory optimization capability may be developed for the full-scale simulation environment to account for operational variability as well as the energy-time optimality of the rendezvous.

• Guidance and Flight Control Laws

Flight control laws are an essential element of the ARAD system responsible for tracking the guidance commands computed by the guidance laws through feedback control of the relative state estimation. The flight control system (FCS) will require several different control structures based on the control system mode, which is controlled by the FMS. The initial implementation of the control law for each control mode will likely be a cascaded single-input single-output linearized control law, which will provide performance guarantees and stability margins. This control law strategy has a well-established path towards V&V and certification of aircraft flight control systems. The second phase of this task will involve evaluating the performance of the FCS against the wind field and rotor downwash models. Wind field and downwash flight control augmentation will be developed based on this analysis.

Challenges associated with the control system development include:

- Stable and energy-efficient controlled flight under intense rotor downwash
- Disturbance rejection control to manage changes in loading, stability and control characteristics, mass, and inertias due to drone docking with battery or power cable
- Stability and control of coupled AAM vehicle-drone system during docking
- Handling qualities and passenger ride qualities during docking
- Flight control augmentation for improved stability, handling qualities, and passenger ride qualities, if necessary, by leveraging multi-objective flight control [17]

• Flight Control System Interfaces

The responsibility of this component is to communicate the vehicle-agnostic commands produced by the ARAD system. For the sub-scale flight demonstration goals, a Pixhawk module will be developed. For full-scale high-fidelity simulation goals, a visual scene-based interface will be developed to integrate with the FCS in simulation.

4) Subscale Flight Demonstration

A series of sub-scale flight test demonstrations will be planned to demonstrate feasibility of the ARAD system for AAM energy augmentation. These flight demonstrations will utilize existing NASA sUAS vehicles as sub-scale surrogates. Several candidate NASA vehicles are available to support these flight demonstrations and already have the requisite hardware (sensors, secondary processors, etc.). Flight tests will be conducted in a high bay hangar facility at NASA Ames Research Center with a mockup of an AAM vehicle and docking mechanism attached to the overhead crane system. Relative navigational markers will be developed and installed for a vision-based identification and tracking system. The markers may likely consist of a pattern of IR LED lights and visual-target markings. The dimensions of the coarse-mode navigation marking will likely need to be at least an order of magnitude larger than the fine-mode navigation markings.

Four flight demonstrations are proposed as follows:

1. Rendezvous and horizontal docking maneuver in still air, shown in Figure 15
2. Rendezvous and vertical docking maneuver in still air, shown in Figure 16
3. Heavy tether rendezvous and docking maneuver in still air, shown in Figure 17
4. Rendezvous and docking maneuver under simulated downwash, shown in Figure 18

The major system components of the flight tests are:

<u>• AAM Vehicle Mockup</u>

The AAM vehicle mockup structure minimally needs a set of lights/markers installed at permanent locations along the ceiling of the hangar to support coarse/far-field navigation. The markers and lights need to be sized to be at the expected dimensions of the full-scale AAM vehicle. A fiberglass structural mockup may also be developed to simulate the outer-mold-line structure of the bottom of the fuselage of a candidate AAM vehicle.

The coarse-mode navigation target will be as large as possible to assist with far-field maneuvering (e.g., IR LED lights on the maximal extent of the vehicle airframe structure, which may include existing vehicle navigation lights on the wing tips).

<u>• Docking Mechanism Mockup</u>

The docking mechanism mockup will include a set of markers for fine-mode near-field maneuvering. The fine-mode navigation targets may consist of LED IR lights and patterns placed on the docking structure to support near-field maneuvering requirements.

The docking mechanism mechanical design to enable physical connection of the battery or power cable to the AAM vehicle interfaces is beyond the scope of the ARAD system at this time.

The docking mechanism will be utilized to demonstrate an autonomous precision rendezvous and docking system that can satisfy a horizontal docking maneuver and vertical docking maneuver.

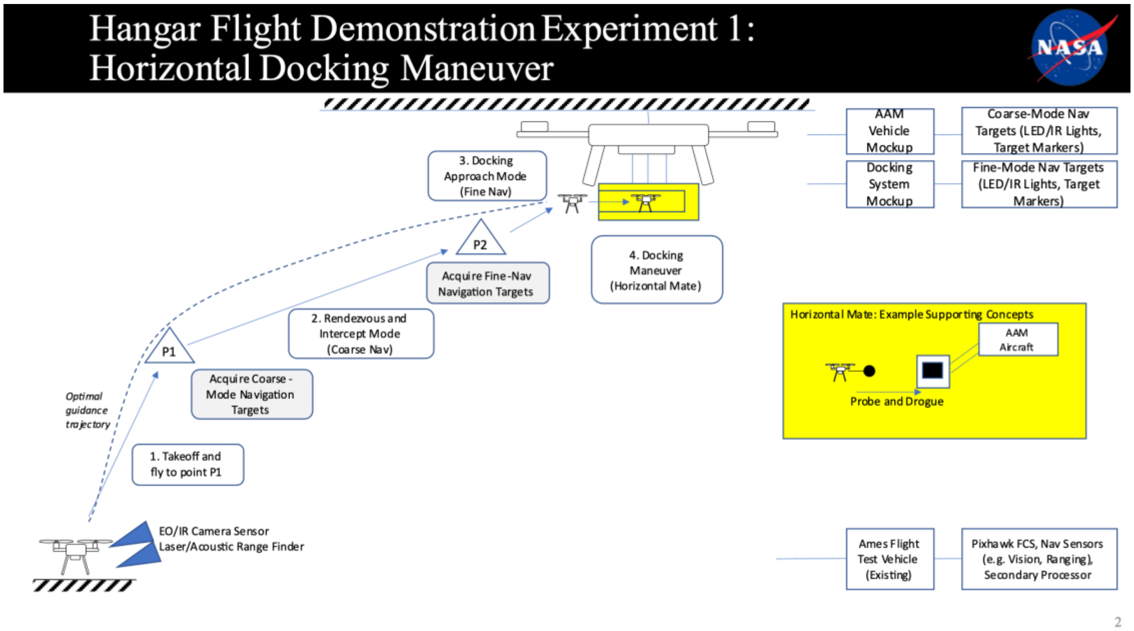

Figure 15: Rendezvous and Horizontal Docking Maneuver with FMS Flight Control Modes Shown.

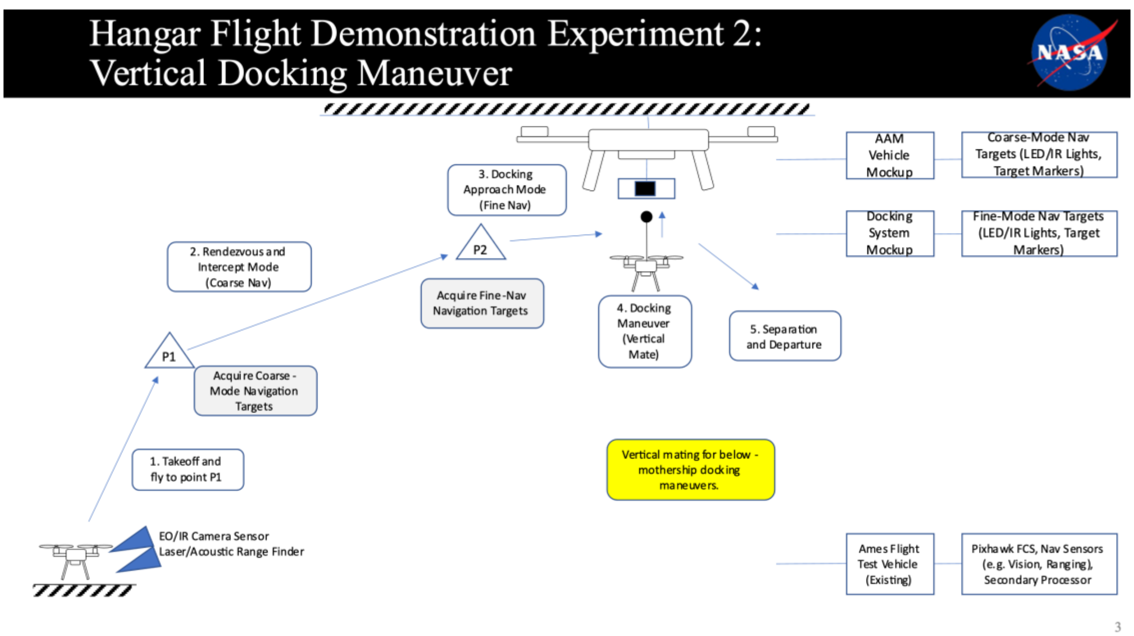

Figure 16: Rendezvous and Vertical Docking Maneuver.

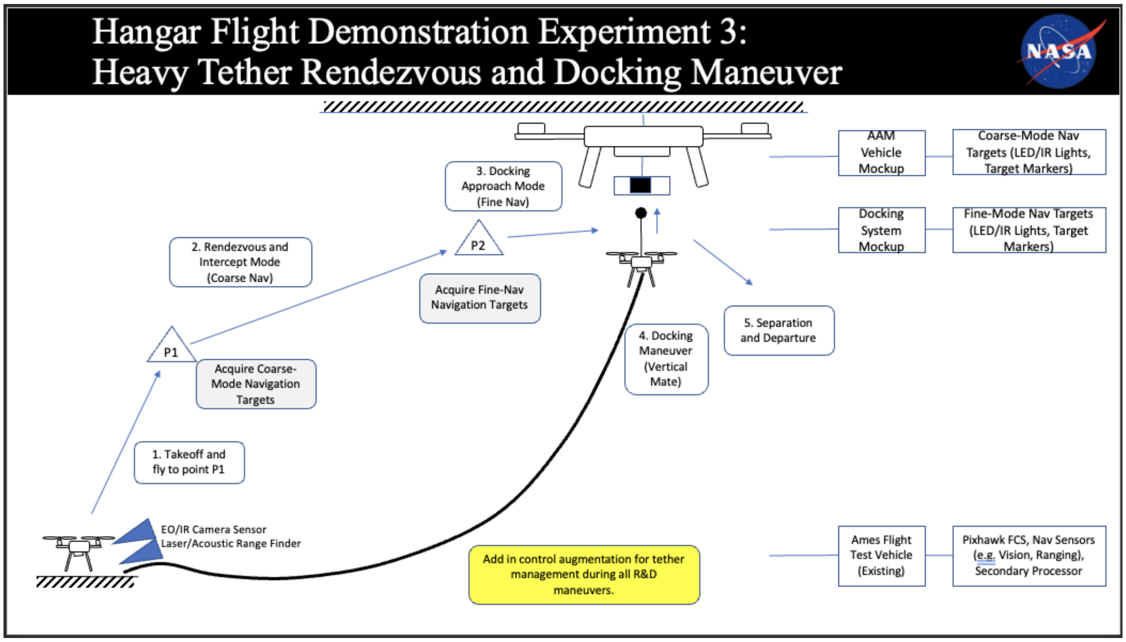

Figure 17: Heavy Tether Rendezvous and Docking Maneuver.

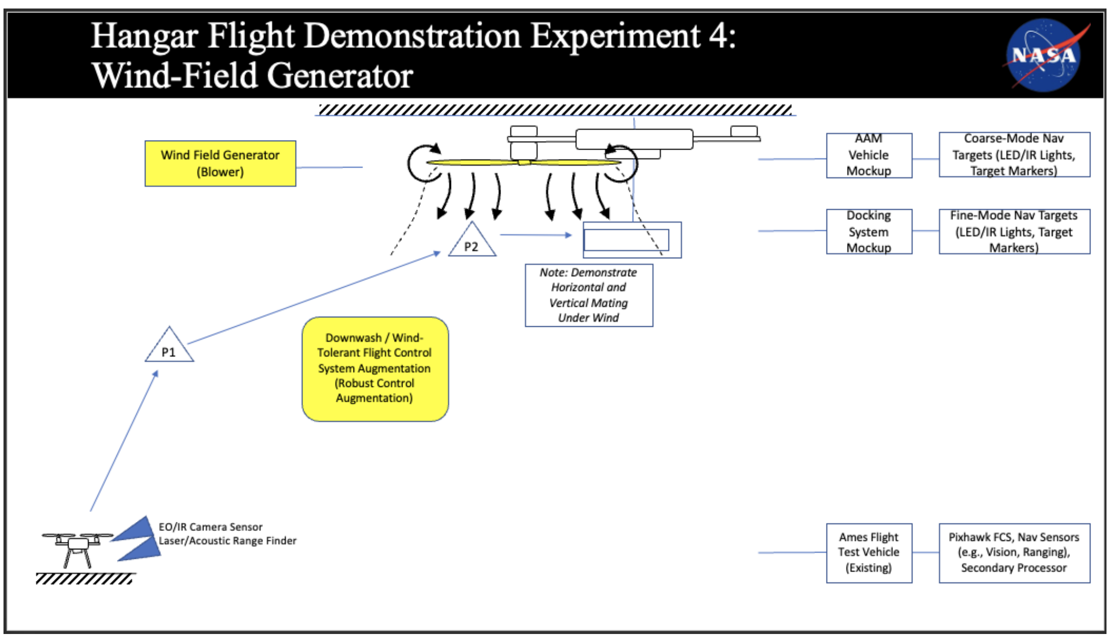

Figure 18: Rendezvous and Docking Maneuver under Simulated Downwash.

For the purposes of the flight demonstration activities, the docking mechanism will be minimally simulated. Minimally, the docking mechanism may consist of a pole extended from the test vehicle with a ball at the end to simulate a probe, and the AAM vehicle-side mechanism may consist of a target with a black rectangle painted on it, for instance representing the 'drogue' in a probe-and-drogue docking approach. The horizontal docking mechanism may also include a bay or cage structure that the vehicle flies into to make a docking maneuver. As part of future technology maturation, this capability could be immediately transferrable to full-scale flight tests on a full-scale vehicle, such as a manned helicopter, to demonstrate full-scale drone-to-aircraft mid-air docking in a potential future follow-on effort.

3. Barriers

The development of ARAD capability for AAM energy augmentation addresses several technology barriers. These barriers can present technical challenges that affect the viability and feasibility of the AAM energy augmentation. Some identified barriers are:

The viability of AAM energy augmentation is predicated upon a positive end-to-end efficiency (V) which needs to account for safety considerations of autonomous rendezvous. The system analysis will examine the end-to-end efficiency question and evaluate the potential energy efficiency gain, if any, against potential safety issues associated with autonomous rendezvous. Since passenger safety is of highest priority, the viability of the AAM energy augmentation will require a high level of safety and reliability for the autonomous rendezvous which implies that technology development should demonstrate a path toward flight certification. Flight control laws should be implemented in a single-input-single-output design to provide quantifiable performance guarantees and stability margins. Algorithms must be rigorously verified and validated to ensure trustworthiness.

The feasibility of the drone delivery approach with flying battery or power cable, will be addressed by the vehicle system dynamics, stability, and control assessment (F). If the battery is to be docked from the underside of the fuselage of the AAM vehicle, the battery will be mounted on the top of the drone. Stability and control of the drone can be compromised, thereby rendering the technical approach infeasible.

The controllability of the drone during rendezvous to the AAM vehicle under intense rotor downwash as well as cross wind and turbulence (F) will determine the overall feasibility of the autonomous rendezvous. The highly dynamic environment during rendezvous and docking perhaps presents the greatest barrier to the implementation of autonomous rendezvous capabilities. The development of the ARAD system will study this feasibility question through system dynamic modeling and control. The FCS development will consider various strategies to address the technical challenges.

The power demand and energy consumption of the drone during autonomous rendezvous and docking under rotor downwash, cross wind, and turbulence may limit the viability and feasibility of the autonomous rendezvous (V/F). The drone carrying the battery or flying battery will likely weigh several hundred pounds or more. The power demand from the rendezvous maneuver through the rotor downwash and docking maneuver with the AAM vehicle subject to cross wind and turbulence may result in high level of battery charge consumption. This could limit the flight operations and the viability of the energy augmentation solution.

The rendezvous and docking flight operations for the power cable should demonstrate high level of energy efficiency (V) to make the concept viable. This is due to the consideration of the charging time with the power cable versus the consumption of the on-board battery charge during hover operations. The power level delivered by the power cable should result in relatively fast charging cycles to minimize the on-board battery charge depletion.

4. Criteria

The effectiveness of the autonomous rendezvous capabilities will be assessed in simulations for full-scale vehicle energy augmentation flight operations and sub-scale flight demonstrations of a subset of the capabilities. Safety (D), passenger ride comfort (D), and end-to-end efficiency (V) will positively influence the public acceptance of the energy augmentation solutions. These influence factors will be evaluated by the following criteria:

End-to-end efficiency should be significantly greater than AAM without energy augmentation. This metric should include time, range, payload capacity, and energy expenditures for all system components, including drone and vertiport infrastructure.

Safety metrics will be obtained to provide quantifiable measures of the impact of the autonomous rendezvous flight operations on the safety of the AAM vehicle. Safety is defined to be any event that can compromise the nominal operations of the AAM vehicle and structural integrity of the vehicle. The ability to precisely navigate through the rotor downwash and follow a pre-defined trajectory without a significant departure from the intended flight path could constitute a safety metric. During docking operations, the AAM vehicle should have good handling qualities and flight control performance measures compared to the nominal values. To evaluate these metrics, uncertainty in the rotor downwash will be included in the full-scale simulation to capture the probabilistic outcomes of the autonomous rendezvous and docking.

Passenger comfort and safety perception are overriding factors that influence the public acceptance of the energy augmentation solutions. Passenger comfort is defined by ride qualities which will be assessed in the execution event. Safety perception may be related to ride qualities which are a measure of the acceleration in the aircraft cabin and also may be related to other factors such as the duration of the energy augmentation flight operation, visual sighting of the drone, and any unexpected events caused by the rendezvous and docking. Some of these factors may be difficult to quantify, but flight control performance measures might be considered.

Benefit and Risk Analysis

ARAD is an enabling capability for direct energy augmentation. As with any technologies, it offers advantages and benefits as well as disadvantages and risks. These benefits and risks need to be traded off to determine the viability and feasibility of ARAD in relation to other competing energy augmentation concepts. This determination could help assess the desirability of the proposed technology in terms of the overarching goals of maintaining flight safety and achieving end-to-end efficiency.

Advantages

- ARAD is perhaps the most realistic capability with the highest technology readiness for direct energy augmentation via in-flight battery exchange or charging with power cable.
- Direct energy augmentation perhaps offers the highest level of desirability in terms of passenger safety and end-to-end efficiency by eliminating the risks of radiation exposure to humans and the low charging rate barrier associated with the indirect energy augmentation via power beaming.
- ARAD can be built upon the proven technology of aerial refueling since the concept of flying a power cable up to an AAM vehicle could employ similar drogue-and-chute idea in aerial refueling.
- Autonomous flying battery swapping using sUAS has already been investigated and demonstrated by universities [20-23]. Those studies can pave the way for extending the autonomous capabilities for flying batteries for AAM vehicles using large drones.
- The certification path for ARAD is relatively straightforward since ARAD is based on GNC technologies for which certification frameworks already exist in contrast to safety

considerations for human passengers under long-term radiation exposure for which new certification processes may need to be developed.
- The public perception of ARAD is likely to be much more favorable than that of indirect energy augmentation with power beaming since long-term radiation exposure is generally viewed by the public as a health concern.
- The likelihood of technology adoption of ARAD may be higher than that of indirect energy augmentation.

Disadvantages
- Operating a large drone in close proximity to an AAM vehicle can increase collision risk.
- ARAD for in-flight charging with power cable can pose flight safety risks to AAM vehicles due to power cable dynamic response to atmospheric gust or turbulence.
- Drone operation with heavy battery payloads weighing several hundred pounds under the direct rotor downwash could potentially be challenging, thereby necessitating more complex trajectory execution which may consume more battery life.
- The potential increased complexity in battery connect and disconnect mechanisms could pose a safety concern of potential power loss in the event of faulty battery connection.

5. Anticipated Outcome

The ARAD system will serve as a prototype system for further ARAD development which could lead to a full-scale flight demonstration program. The flight test data will be used to validate sub-scale simulation models to provide performance and stability robustness measures of the ARAD system. These measures will be used to refine or quantify the safety metrics. The outcomes of this research could also be used to provide input to further refine the concepts of operation.

The stakeholders that are primarily supported through the development of the ARAD capability include vertiport passengers and operators, AAM operators, and NASA aeronautics research projects. The development of the ARAD capability provides safe and energy-efficient enabling capabilities for direct energy augmentation methods which will enhance AAM operations without significant impacts on safety.

6. Stakeholder(s)

The primary stakeholders that are supported through the development of the autonomous rendezvous capabilities are vertiport passengers and operators (D), AAM operators (V), and NASA (F). The development of the autonomous rendezvous supports vertiport operators, passengers, and AAM operators by providing safe and energy-efficient enabling capabilities for supporting energy augmentation solutions that will enhance their operations without significant impacts on safety. The autonomous rendezvous supports NASA by defining a set of operationally representative conditions and missions that will be incorporated into full-scale simulation models, test hardware, and sub-scale flight demonstration activities.

Aerial Docking Demonstration

1. Purpose

The Aerial Docking Demonstration (ADD) activity examined several of the energy augmentation concepts that were considered to identify opportunities for near-term flight demonstrations that would provide value by addressing barriers specific to these concepts. The common aspects of these concepts were a) the delivery of additional electric power to the aircraft would be accomplished through a physical connection and interface on the outer surface of the vehicle and b) the connection to that interface could be established or broken while the aircraft was in flight. This included concepts such as carrying a power tether up to attach to a hovering aircraft or launching a "flying battery" that would rendezvous and dock with an aircraft in flight to supplement its power. The goal of ADD was to assess the Desirability, Viability, and Feasibility of near-term, scale demonstrations of these concepts from the perspectives of the various stakeholders that need to see value in a proposed CAS project.

2. Method Approach

The flying battery and cable power energy augmentation concepts were explored to identify barriers that would need to be addressed for it to be successful, whether they were technical, financial, or cultural barriers, as shown in Figure 7. The ADD effort included demonstrating mid-air docking and undocking of a flying battery, demonstrating safe tether management, developing and implementing safety models for automated aerial docking (as shown in Figure 19), and designing demonstration that had the potential to build industry confidence in one or more of the concepts and justify further development.

Additionally, each Aerial Docking Demonstration had to be assessed with regard to whether a CAS effort could address the identified barriers in a meaningful way within the financial and time constraints of a typical CAS project. From a project resources perspective, a typical CAS effort would be executed by a 4-6 person team, require modest capital investments from NASA, leverage existing facilities and capabilities, and be completed in two years or less. These CAS execution effort scope considerations were explored by evaluating what kinds of commercially-available or partner-provided hardware could be used, what facilities might be available, who would be available to work on the project, and so on. The progress of this work was socialized within the EAVES team, with CAS management, and with others outside of NASA, to gather feedback, and discover new constraints, challenges, or opportunities.

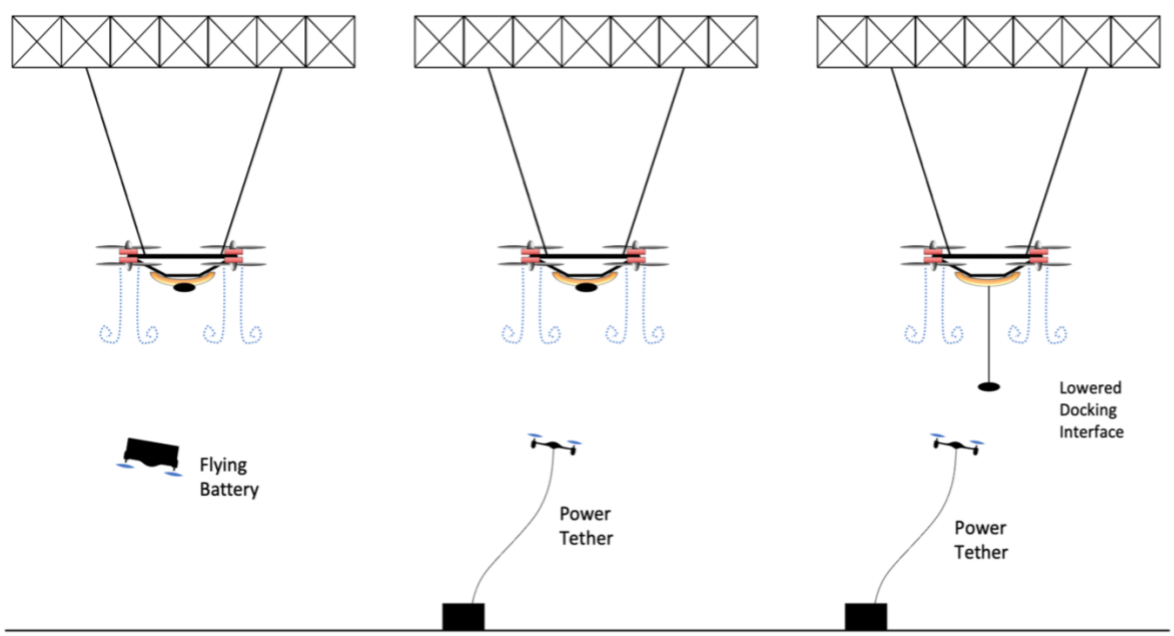

Figure 19: A variety of augmentation concepts and operational scenarios can be addressed with this approach.

The barriers and concerns most relevant to Aerial Docking concepts for passenger aircraft that revolve around safety, technical feasibility, and efficacy. From a general public perspective, a successful Aerial Docking system would have to operate with a high degree of authority and precision in a complex and chaotic environment to inspire confidence. If the system in action looks chaotic or as though it is operating at the edge of its capabilities, the public will not ride on aircraft that use it. This elevates the Public Perception and Trust barriers above the other shared barriers for ADD, as knocking down all of the other barriers will be a wasted effort if it is never used.

Moving to the CAS Execution Barrier perspective, funding a public flight demonstration of an Aerial Docking system that routinely performs successfully with authority and precision would be an effective way to directly address the Public Perception and Trust barriers for this group of augmentation concepts. Seeing would be believing if the flight demonstration was routinely successful when operating near full scale in challenging flight environments.

The critical elements of such a demonstration would be: high-speed precision tracking and guidance systems to manage docking and undocking in flight, a sufficiently agile docking vehicle with the control authority to accomplish the required maneuvers, a functional physical docking/undocking interface, a mock-up of the electrical power interface, and a method of generating realistic flow fields for the flight demonstrations.

An opportunity concept was developed where the resulting CAS effort's technical work would be done at a range of scales. Early activities would evaluate concepts economically and efficiently at smaller scales and use those experiences to guide and inform designs (e.g., capture mechanism selection) and programmatic decisions (e.g., Persevere, Pivot, or Punt (P3) decision points) regarding follow-on demonstrations at more relevant scales.

Proposed approach would begin with ground actions to design, prototype, and test concepts for the various elements of the demonstrations. Central to this work would be a focus on ensuring that the systems were sufficiently instrumented for the test data to inform and guide the internal work of the team and address any industry concerns about the technical value of the demonstrations.

Each flight demonstration would include an aircraft "iron bird" that would be suspended from an overhead structure to emulate a hovering VTOL aircraft (see Figure 20 below). It would provide outer mold line surfaces around the docking interfaces as well as providing downward propulsive thrust (and accompanying flow field) consistent with a hovering aircraft.

Initial testing, integration, and demonstration activities would focus on the elements of quarter-scale demonstration system with an “Iron Bird Alpha” at its center. A series of low-cost iron bird prototypes would be used to evaluate how far the various subsystem elements could be scaled up to approach a full-scale demonstration within the resource and time constraints of the project. The iron bird for the final demonstration would be christened Iron Bird Omega to signify it being the last of the series.

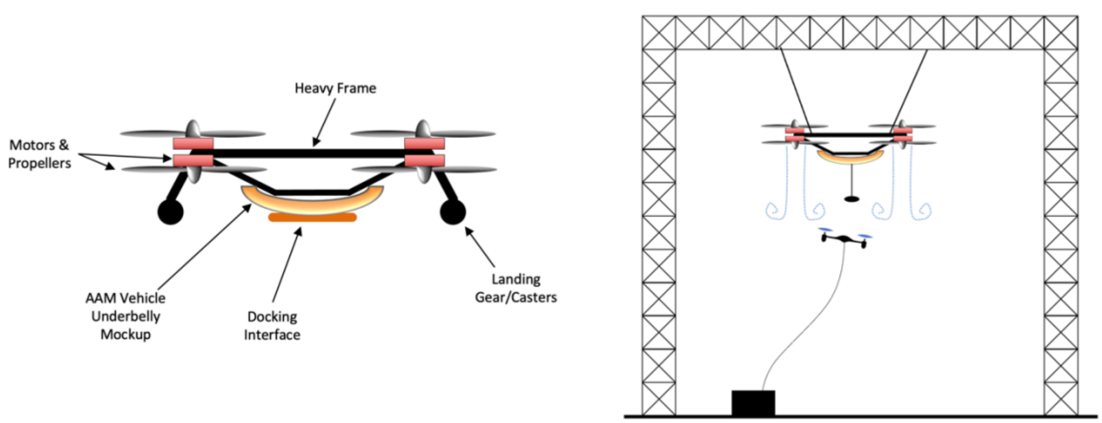

Figure 20: Concept sketches of the “suspended iron bird” concept.

To align with CAS resource levels and timelines, every effort was made to leverage existing equipment and facilities to accomplish the work. The project execution concept was to develop and prove the common critical elements and integrate them in a flight demonstration called the Quarter-Scale Demonstration. The results of that work would inform decisions of whether to and how to proceed with the development of any Large-Scale Demonstration (see below).

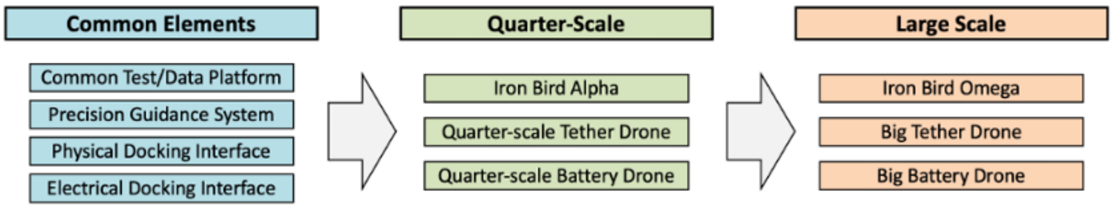

Figure 21: Proposed project elements and the progression to testing at larger scales.

Specific supply chain challenges were identified with regard to acquiring the motors and electronics necessary to create full-size AAM vehicle flow fields in a hover. The availability of AAM-sized brushless motors and motor controllers is currently an industry-wide problem and part availability may be the deciding factor for what the actual scale of a Large-Scale Demonstration would be for a CAS project timeline.

The proposed project concept included project elements to address any of the augmentation concepts included under the "Aerial Docking Demonstration" umbrella but assumed that only one or two of the concepts would be selected for demonstration during the execution of the activity.

3. Barriers

Several barriers were identified and assessed when considering whether there are opportunities for CAS to advance these concepts. From the perspective of a proposed CAS project, aerial docking demonstrations would need to directly address major barriers with an acceptable commitment of time and resources. Along with the shared barriers shown in Figure 7, which were common to all the energy augmentation methods considered, additional barriers were identified that are specific to concepts that involve aerial docking. These additional barriers were selected to be addressed by the proposed effort are:

- Mid-air docking/undocking for vehicles with very different mass properties.
- Safe tether dynamics management during docking operations.
- Implementing safety models and systems that will produce safe outcomes in a wide variety of off-nominal conditions.
- Public acceptance of aerial docking as a form of AAM energy augmentation.
- Industry acceptance of aerial docking for AAM energy augmentation.

These additional barriers emerged from considering different stakeholder perspectives for a wide array of challenges to performing safe, routine, inflight docking, and undocking operations. A series of near-term aerial demonstrations showing routine aerial docking and undocking events in a realistically challenging flight environment, between vehicles that were near full scale, would capture the attention of both the public and industry. This could be the first step toward establishing public confidence in the demonstrated concepts while also spurring interest in the aerospace industry, which would need to invest years of resources and development to eventually make the demonstrated concepts a reality in commercial aviation.

Technical implementation details of the systems performing the aerial docking demonstrations would determine how seriously they would be taken by industry and shape their impact. Addressing the additional barriers that are technical in nature would establish the credibility of the demonstrations and concepts for those stakeholders. These would be addressed through architecting and demonstrating a proof-of-concept safety approach that successfully collects, integrates, and acts upon real-time data streams to produce predictable, safe outcomes for close proximity operations.

4. Criteria

At the highest level, success for the Aerial Docking concepts would be flight demonstrations that convince the public and industry that this mode of energy augmentation is a reasonable approach, worthy of further investment, so it could take its place in commercial aviation someday. One measure of this would be the levels of industry and public press coverage of the flight demonstrations and whether the demonstrated concepts are portrayed as "crazy and far out" or "exciting and new."

Success as a CAS effort would be clean execution of the work necessary to attempt these demonstrations, returning a clear signal as to whether this approach shows promise. Part of that success would result from the "down and in" technical work that produces the flight demonstrations. An equally important part of that success would be the "up and out" socialization of the concepts and the team's activities with prospective users and potential industry partners. If the effort's results indicate there are attractive opportunities for further investments and development, relationships with potential partners and initial plans for next steps would be additional markers of success.

5. Anticipated Outcome

At the end of the effort, the Aerial Docking Demonstration team would work with CAS to assess the effort and explore next steps.

6. Stakeholders

The general public and aircraft passengers are always prominent stakeholders in aviation research. For efforts working on concepts at lower Technology Readiness Levels (TRLs), the stakeholders would be AAM avionics and propulsion system developers, AAM startups, and prospective AAM aircraft operators, who will be most directly impacted by advances in this area.

Microwave Power Beam Indirect Charging

1. Purpose

The Energy AugMentation PoweR BEaming Safety Study (EMPRESS) activity will act as a safety and performance pathfinder for the safe delivery of “on-demand power” to AAM platforms utilizing a cost-effective Radio Frequency (RF) power beaming technology prototype. This effort will develop and evaluate the operational safety, power efficiency, flight scenarios, hazard containment and mitigations necessary to enhance the power distribution flexibility and resiliency at future AAM vertiports. In addition to personnel safety, power performance and distance metrics will be reported in a subsequent report. Most power beaming research activities are evaluating applications of power beaming without human presence; this activity is primarily focusing on power beaming with humans in proximity, which presents new challenges.

2. *Method Approach*

This study will focus on developing an operationally representative test scenario for an AAM in static hover flight simulating a holding pattern. This maneuver was selected because it requires the most power within the AAM vehicle flight profile at the vertiport.

There will be three distinct phases for this activity to effectively assess power beaming in a static horizontal flight mode test simulation. The initial phase will focus on the development of a scalable, modular Energy Augmentation System (EAS) capable of supporting power beaming applications and/or integrating into an aerial platform for use at a vertiport. At the end of this phase, a determination will be made to proceed with a partnership-based approach. The second phase consists of completing the partnership process. The final phase of this activity consists of conducting the power beaming test and generating a report.

Each power test will include the following six tasks in each phase:

1. Ensure the transmitter and receiver hardware have the necessary power handling capability
2. Ensure the power network handles interruption failures without catastrophic effects
3. Ensure the network delivers power from point to point
4. Evaluate the impact from transmission turbulence and measurement noise between transmitter and receiver
5. Evaluate the impact of real-time power monitoring and send/receive capabilities
6. Measure E-field and RF incident power/field intensity profile at receiver for each transmitter configuration and geometry orientation.

3. *Barrier(s)*

The EMPRESS method primarily addresses the following barriers:

- Power conversion inefficiencies causing excess thermal loading (D/F)
- Human safety/radiation emission containment (irradiance levels exceeding 5 mW/cm) (D/F)
- Public perception of Energy Augmentation (D)
- Additional aircraft weight/power system accommodation (V/F)
- Additional up-front investment from AAM users and vertiport operators (V)
- Spectrum/EMI interference & availability (V/F/W)
- Energy delivery on demand (W)
- Airspace complexity and battery charge/charge time (W)

4. *Criteria*

The criteria used for effectiveness of the EMPRESS activity are described with appropriate parameters required for the barriers described above (see Table 2 below). It is observed from the table parameters that each of the barriers described above can be addressed. The parameters are split into energy characteristics and AAM personnel safety. These criteria generally can be used for other indirect charging methods as well. It will be expensive and will require several years' worth of effort to compare and compute each of these parameters and their efficacy. Details on the computations will be reported in a future report once the investigation is underway.

Table 2: Description of parameters required to address barriers.

Parameter	Description
Energy Characteristics	
D_{TX}	Maximum dimension of the transmitter aperture
λ (m)	Wavelength at the frequency of operation
d_{TRX} (m)	Distance between the transmit and receive apertures
D_{RX} (m)	Maximum dimension of the receiver aperture
$P_{TX\text{-}in}$ (W)	The power from all input sources to the transmitter
$P_{TX\text{-}out}$ (W)	Transmitter power output at frequency of operation
$P_{RX\text{-}in}$ (W)	The power incident on the receive aperture
$P_{RX\text{-}out}$ (W)	The arithmetic mean power at the output load
$p_{d\text{-}max}$ (W/m^2)	The maximum power density along the beam's path
$p_{d\text{-}acc}$ (W/m^2)	The maximum power density accessible to people animals, aircraft, etc.
m_{TX} (kg)	The mass of the transmitter and transmit aperture
m_{RX} (kg)	The mass of the receiver and receive aperture
V_{TX} (kg)	The volume of the transmitter and transmit aperture
V_{RX} (kg)	The volume of the receiver and receiver aperture
t_o (s)	The duration over which the demonstration occurred
AAM Personnel Safety	
T_{EC}	Exterior cabin temperature
T_{IC}	Interior cabin temperature
R_{EC}	Exterior Radiation/EMI
R_{IC}	Interior Radiation/EMI

5. Anticipated Outcome

At the conclusion of the EMPRESS activity, the team will characterize the safety of an MW power beaming system to an AAM platform, uncover other safety barriers not previously known, and characterize the efficiency of the system to make a business case for further development. This activity will be the first step to understand the desirability, viability and feasibility of a power beaming system that is designed to power aircraft with human passengers and crew.

6. Stakeholder(s)

The stakeholders that are primarily supported through the EMPRESS development are AAM passengers, vertiport operators, and electric utility providers (D), FAA, AAM operators and cargo delivery (V), FAA & Federal Communications Commission (FCC) (F), and NASA (W). The EMPRESS activity supports vertiport operators and FAA/AAM personnel by providing an assessment of indirect energy augmentation modalities that could improve safety, vehicle range, efficiency and reduce the carbon footprint of AAM operations.

Conclusion

This Technical Memorandum reported on the energy augmentation concepts considered for recharging the Advanced Air Mobility electric air vehicle before it reached its destination. This research was conducted by the authors over a six-month period as a part of the Convergent Aeronautics Solutions (CAS) Project's Planning phase. Five direct charging and three indirect charging concepts were presented. The implementation is intended for the year 2045 timeframe.

For the four methods selected for further investigation—the Study of Energy Augmentation Methods and Airspace Complexity (SEAMAC), the Autonomous Rendezvous and Aerial Docking (ARAD), Aerial Docking Demonstration (ADD), and Energy Augmentation for Power Beaming Safety Study (EMPRESS), each of the following six perspectives were addressed: 1) Purpose, 2) Method Approach, 3) Barriers, 4) Criteria, 5) Anticipated Outcome, and 6) Stakeholders. While considering the concepts, the barriers were assessed based on the attributes of Desirability, Viability, Feasibility, and Wickedness. Some other barriers like thermal management were not addressed, as they were considered out of scope for this effort. This research was presented at the 2023 SciTech Forum in National Harbor, MD in January 2023 [24].

It was decided during the final Persevere, Pivot, Punt (P3) decisional meeting that the EMPRESS research activity will move forward. This decision was made to investigate the indirect charging concept further due to its “wickedness” as a ground-breaking technology and far-reaching applications. As of the writing of this document in August 2023, the EMPRESS effort is underway to define the parameters required for microwave charging of an AAM eVTOL vehicle using a transmitter and a rectenna mounted on the vehicle. A partnership with Defense Advanced Research Projects Agency (DARPA) has been established and collaboration is ensuing. A paper has been accepted for publication and presentation at the 2023 Digital Avionics Systems Conference to be held in October 2023 [25].

Recommended Next Steps

During the course of this research, significant effort was invested in developing the initial concepts, after the survey of direct and indirect concepts. Several concepts, referenced in the Rejected Concepts section above, were not considered due to the perceived inherent limitations of those concepts. It is recommended that those be revisited in due time. Until then, the team, with some changes in membership, will continue to pursue further investigation in the concept of microwave charging for electric air vehicles to determine the potential for implementation.

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