Energy Augmentation Concepts for Advanced Air Mobility Vehicles

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This introductory paper describes several concepts that could be used for augmenting the energy state of electric Vertical Take-Off and Landing (eVTOL) vehicles. Advanced Air Mobility (AAM) electric vehicles, just like conventional vehicles, could need additional charge due to depleted batteries (e.g., strong winds along the way) while approaching their destination. There are three indirect charging and five direct charging concepts presented in this paper. The concepts are in 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 the AAM vehicles. The paper describes more details and discussion on the desirability, viability, and feasibility of these energy augmentation concepts. A discussion of barriers and initial investigation approach for three concepts is presented.

I. 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 plausible designs are available today. The performance profiles and battery characteristics of these AAM vehicles are proprietary and not publicly known. NASA has developed several representative performance models that are being used for simulation purposes [1].

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 capacity that they could be charged to when they depart, and they have limited range. If there is inclement weather or strong winds along the way, or inability to land at the destination (e.g., disabled vehicle on the landing pad), the vehicles would need additional charge to continue their operation if an alternate landing vertiport is not in the vicinity. Also, the depletion rate of the batteries behaves non-linearly at lower charge levels [2]. Low-energy or emergency landing (especially under extreme weather conditions) uses even more energy and is a severe threat to safe AAM operations.

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This paper explores the possibility of directly or indirectly charging AAM electric vehicles as they get closer to their destination or providing an additional boost during the departure phase from the origin Vertiport (termed like an airport, but for vertical take-off and landing vehicles). NASA is exploring these concepts for the 2045 timeframe. In Section II, the concepts being considered for evaluation are presented. Section III provides the barriers addressed for classification of concepts. The selected concepts for further investigation are presented in Section IV. The paper ends with some concluding remarks on the energy augmentation methods for electric air vehicles.

II. Concepts for Indirect and Direct Charging

The current work evaluates two Indirect Charging and five Direct Charging concepts. The following two sections detail the concepts being considered. These concepts have been conceived by researchers based on past literature and currently available mechanisms/processes.

A. Indirect Charging

Indirect Charging or "power beaming" refers to the concepts that do not involve any physical contact (e.g., wireless) between the charging mechanism and the AAM vehicle. In contrast to directed energy applications, the primary goal of power beaming is the safe and efficient transfer of energy instead of producing deterrent or destructive outcomes.

The three modalities for Radio Frequency (RF) power beaming concepts being considered are:

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

1. Optical power beaming refers to using 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.

2. Millimeter (mm) wave power beaming refers to the mechanism under consideration of using 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 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.

3. Microwave (MW) power beaming refers to the mechanism of using 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 Section IV.C.1 for more details). It is also better understood for scaling up size and power. Remote charging would involve wireless energy transfer through microwave transmitter to a phased array rectenna (rectifying antenna) 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.

B. Direct Charging

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

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

1) Charging Platforms are like gas stations for internal-combustion engines or charging stations for electric vehicles along streets or freeway exits. These 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 the AAM vertiports will be at ground level (large dirt patches), or about 50-60 ft high (tops of parking garages), or higher at 200-300 ft (tops of skyscraper buildings), etc. The charging platform being quite tall, would not require as much energy to land from a cruise altitude of 1500-2000 ft (based on currently known AAM vehicles). However, these could be scattered across the cities or rural landscapes where AAM vehicles could recharge to extend their range [3].

These could also be placed strategically to accommodate arrivals and departures from various vertiports, accounting for their direction of flight. These are a one-time expense to build and then cost of 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 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).

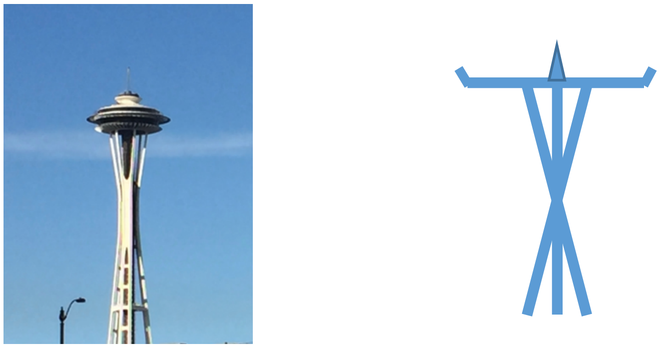

Fig. 1 A potential charging platform sample like the Space Needle (Seattle, WA, height 605 ft)

2) 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 a swappable battery, which could be standardized or specific to the design of that vehicle. This concept does not impact the primary battery charging system because it's for augmentation purpose. 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.

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

3) Due to the dead weight aspect of swappable batteries, flying batteries are considered. This energy augmentation method evolved from the notional concept of floating platforms that could charge eVTOL vehicles, similar to charging platforms on the ground (see 1. 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). Once the charging is complete, the battery would undock and fly back to a docking location on the vertiport or the nearby charging platform, where it originated from. 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 sample battery with a rotor on top (left) and an AAM vehicle with the docked battery at the bottom (right).

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

4) 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. The sway of the cable during unsteady winds, the docking and undocking, and retraction of the heavy cable are all being assessed for feasibility. Figure 4 (below) represents a winch, cable, and a tug-drone approaching an AAM vehicle.

5) Hybrid concept is a combination of the charging platform, swappable batteries, a flying battery, 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 three 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 three concepts simultaneously.

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

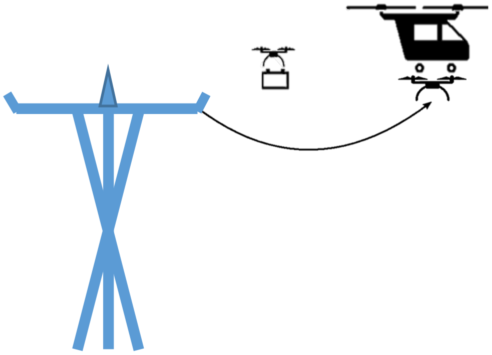

Fig. 5 Hybrid concept as a combination of a charging platform, a flying battery, and cable power.

III. Barriers Addressed for Classification of Concepts

Desirability (interest from invested parties or stakeholders and public), Viability (economic practicability), and Feasibility (technological plausibility) of the concepts are being 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. The 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 addressed across all the proposed concepts for desirability (D), viability (V), feasibility (F), and wickedness (W) 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,
- (F/W) Airspace complexity,
- (F) Additional vehicle weight and drag.

IV. Selected Concepts for Investigation

To mature energy augmentation concepts for AAM, a multi-prong approach is taken to address both direct methods and indirect methods, 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 [4, 5],
- Rendezvous of two autonomous small-scale eVTOL vehicles in operationally representative environment [6, 7],
- Drone and vehicle flight dynamics and control in operationally representative environment [8, 9],
- 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 (laser power) or microwave power beaming to an AAM vehicle.

The first 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 methods under consideration. The ConOps document also determines which energy augmentation methods show the potential for increased operational efficiency at vertiports. Once that document is developed, the following three activities are expected to proceed for further investigation:

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

These activities are being considered 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 next Section.

A. Study of Energy Augmentation Methods and Airspace Complexity (SEAMAC)

1. Purpose

This activity will provide an assessment of the complexity of airspace from an air traffic managers' perspective when various energy augmentation methods are implemented. When the density of traffic increases (e.g., with flying battery autonomous flight), the airspace complexity and the air traffic manager's workload 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.

2. Method Approach

This study will initially focus on activities toward developing a simulation platform/environment of AAM vehicle operations for each energy augmentation method that will be supported by the other three (autonomous flight, in-flight docking, and power beaming) activities. Each scenario session will include the following:

- Description of the operating environment and the dynamic scenario with constraints (F/W)
- Definition of the performance characteristics of the AAM vehicle(s) (F)
- Definition of the physical characteristics of the energy augmentation system (V/F/W)
- Evaluation of the complexity of the defined scenario (F/W)
- Assessment of benefits and limitations (V)
- 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 and 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). This study will recommend effective and low-complexity energy augmentation operations to positively influence public opinion and provide a safety assessment from the 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. This study will help improve the market for eVTOL vehicles and is a critical parameter to ensure airspace access for flight operators and Federal Aviation Administration (FAA) (F). This study will support and recommend methods for AAM energy augmentation activities, while considering varying levels of traffic densities and schedules. Such work has been undertaken for conventional traffic and a preliminary framework exists (see Figure 6 below). Such an assessment 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.) are being developed independently and will be integrated in this effort (W).

5. Anticipated Outcome

The study of energy augmentation method and airspace complexity will be used primarily for internal recommendations and assessment. However, the scenarios and complexity parameters may be released externally through a technical publication at a conference. 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), 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 the NASA requirements by refining the set of operationally representative conditions for test and demonstration planning for the other direct and indirect energy augmentation activities.

Fig. 6 Preliminary design sketch for the SEAMAC activity, with noise contours and battery display.

B. Autonomous Rendezvous and Aerial Docking (ARAD)

1. Purpose

This activity will identify and conduct development of autonomous rendezvous technology to reduce barrier risks for AAM energy augmentation methods. 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.

2. Method Approach

The activity for autonomous rendezvous is supported by four work elements:

1. Systems analysis,
2. Vehicle dynamic modeling,
3. Autonomous Rendezvous and Aerial Docking (ARAD) system, and

4. Subscale flight demonstrations.

The initial concepts to be executed are: 1) flying battery direct rendezvous and docking, and 2) flying power cable direct rendezvous and docking. The flying battery concept is illustrated in Figure 7. The flying power cable concept is similar in execution with the battery replaced by the power cable. Other concepts may be studied if schedule and resources permit. Each of the four work elements is further defined as follows:

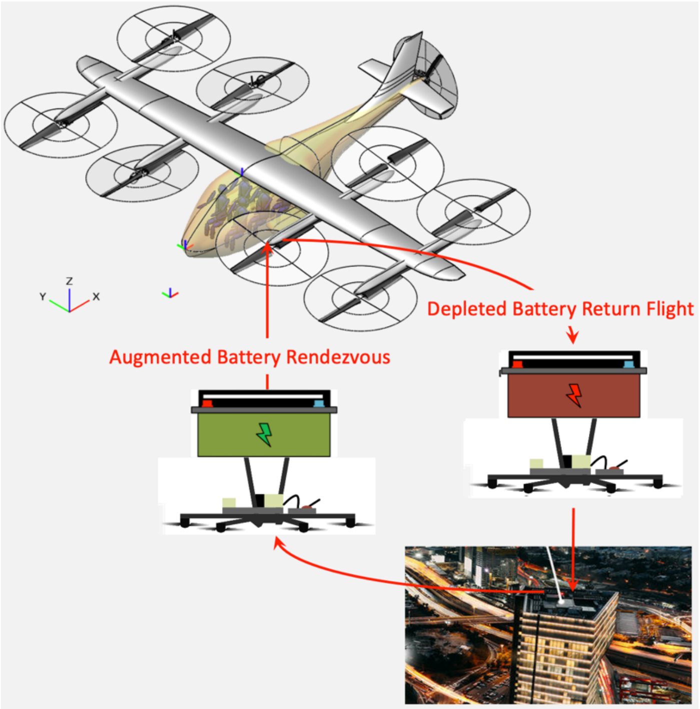

Fig. 7 Display of flying battery autonomous rendezvous and aerial docking concept.

1. Systems Analysis

The systems analysis studies will identify preferred energy augmentation concepts for flight autonomy development. A limited number of potential concepts will be evaluated (flying battery and power cable). The AAM vehicle will be the reference Lift+Cruise vehicle developed by the Revolutionary Vertical Lift Technology (RVLT) project as shown in Figure 7. The tasks to be performed are: 1. estimation of weight, power, and energy requirements for flying battery and power cable, 2. sizing of drone for flying battery and power cable, and development of performance model, 3. assessment of effect during docking on the performance of the AAM vehicle, and 4. conducting end-to-end efficiency studies.

2. Vehicle System Dynamic Modeling

To assess the viability and feasibility of the energy augmentation methods and support the ARAD flight autonomy system 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 tasks to be performed are: 1. development of 6-dof flight dynamic models of AAM vehicle and flying battery/power cable-carrying drone, 2. development of a dynamic model of power cable sway under tension and aerodynamic loading, 3. modeling of rotor downwash in hover and forward flight, and 4. assessment of stability and control for the coupled AAM vehicle-drone system (see Fig. 8).

3. Autonomous Rendezvous and Aerial Docking (ARAD) System

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 point of rendezvous 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 with the AAM vehicle. The tasks for this work are:

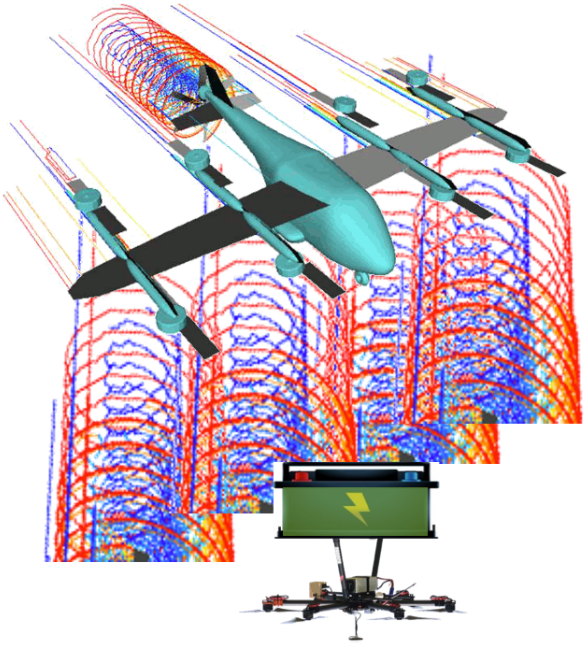

Fig. 8 Depiction of downwash model of AAM vehicle in hover with drone in downwash.

1.implementation of the Flight Management System (FMS) for coordination between various ARAD subsystems, 2. selection of specific algorithms for detection and tracking based on the design of the fine-mode and coarse-mode targets developed for docking, 3. development of optimal filters that combine Inertial Measurement Unit (IMU), magnetometers, and airspeed data sensor measurements for relative navigation estimation module, 4. development of flight control system interfaces to communicate the vehicle-agnostic commands produced by the ARAD system.

4. Sub-scale Flight Demonstrations

A series of sub-scale flight test demonstrations will be planned in support of this activity 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 on hand and available to support these flight demonstrations and already have the requisite hardware (sensors, secondary processors, etc.). Flight tests will be conducted in facilities at NASA with a mockup of an AAM vehicle and docking mechanism attached to an overhead crane system. Three flight demonstrations are proposed but are subject to change based on schedule and resources.

3. Barrier(s)

The development of autonomous rendezvous capabilities for AAM energy augmentation addresses several barriers. The viability of the AAM energy augmentation is predicated upon a positive end-to-end efficiency. The feasibility of the drone delivery approach with flying battery or power cable will be addressed by the vehicle stability and control assessment. Since passenger safety is of highest priority, the viability of the AAM energy augmentation will require a high level of flight safety and reliability for the autonomous rendezvous which implies that technology development should demonstrate a path toward flight certification. The highly dynamic environment during rendezvous and docking perhaps presents the greatest barrier to the implementation of autonomous rendezvous capabilities. The battery charge availability 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. The rendezvous and docking flight operations for the power cable must demonstrate a high level of energy efficiency to make the concept viable. This is due to the consideration of the charging time with the power cable versus the on-board battery charge depletion during hover operation.

4. Criteria

The criteria to determine 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) is required for the public acceptance of the energy augmentation solutions. These influence factors will be evaluated by the following criteria: 1. End-to-end efficiency should be significantly greater than AAM without energy augmentation. The metrics should include time, range, payload capacity, and energy expenditures for all system components include drone and vertiport infrastructure. 2. Safety metrics will be obtained to provide quantifiable measures of the impact of the autonomous rendezvous flight operations on safety of the AAM vehicle and people/property on the ground. 3. Passenger comfort and safety perception are overriding factors that influence public acceptance of the energy augmentation solutions. Passenger comfort is defined by ride qualities. Safety perception may be related to ride quality which are a measure of the acceleration in the aircraft cabin and 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.

5. Anticipated Outcome

The outcomes of this activity will be full-scale simulation models and results, the hardware implementation of the ARAD system and the flight test data acquired from the sub-scale flight demonstrations. The outcomes of this activity could also be used to provide input to the other activities, such as the CONOPS and airspace complexity. Dissemination of the outcomes of this activity will be through technical publications and presentations at conferences.

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 impact 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.

C. Energy AugMentation PoweR BEaming Safety Study (EMPRESS)

1. Purpose

The 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.

Three types of power beaming modalities within the RF spectrum (laser, millimeter wave and microwave (MW)) were evaluated to determine which method has the lowest feasibility barriers. 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, is perceived to be safer, and has higher 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 ($\lambda = 1$ m) up to 300 GHz ($\lambda = 1$ mm), wavelength band within the RF spectrum. Thus, overall, MW is a better choice for static flight operations at shorter distances, and laser power beaming is better suited for dynamic flight operations at longer distances, as shown in Table 1 [10].

	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 Required due regard, pointing, user perception	OK	Good	Good
Economy of Scale Based on present state of the art to deliver 1000s of kW over 1000s of km	Poor	Poor	Good

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

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 network delivers power from point to point
4. Evaluate the impact from transmission turbulence and measurement noise between transmitter and receiver
5. Evaluate 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 is primarily addressing 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 user and vertiport operator (V)
- Spectrum/EMI interference & availability (V/F/W)
- Energy delivery on demand (W)
- Airspace complexity, 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 is expensive and several years' worth of effort to compare and compute each of these parameters and their efficacy. Details on the computation will be reported in a future report once the investigation is underway.

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 & FCC (F); 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.

Parameter	**Description**
Energy Characteristics	
D_{TX} (m)	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} *(m^3)*	The volume of the transmitter and transmit aperture
V_{RX} *(m^3)*	The volume of the receiver and receive aperture
t_o (s)	The duration over which the demonstration occurred
AAM Personnel Safety	
T_{EC} (C)	*Exterior cabin temp*
T_{IC} (C)	*Interior cabin temp*
R_{EC} (W/kg)	*Exterior Radiation/EMI*
R_{IC} (W/kg)	*Interior Radiation/EMI*

Table 2 Description of parameters required to address barriers.

V. Concluding Remarks

This paper embarked on a research effort to begin addressing energy augmentation methods for AAM vehicles, specifically, electric Vertical Take-Off and Landing aircraft. Insufficient fuel (i.e., battery charge) is a key risk associated with the operation of these vehicles, especially during the landing phase of flight. The research started with eight (three indirect and five direct) energy augmentation concepts. The aspects of desirability by stakeholders and general public, economic viability, technical feasibility, and wickedness, were considered for the initial concepts. These led to the assessment of various barriers, e.g., rendezvous flight autonomy, airspace complexity, end-to-end efficiency, with the concepts classified into three main activities.

Based on the initial effort of developing the Concept of Operations, these activities will be guided for further investigation. The current understanding and development plans for the Study of Energy Augmentation Methods and Airspace Complexity (SEAMAC), Autonomous Rendezvous and Aerial Docking (ARAD), and Energy Augmentation Power Beaming Safety Study (EMPRESS) activities are presented. The outcomes of the analyses being conducted currently are expected to lead to technical demonstrations that seek to reduce or eliminate barriers to the development of indirect and direct energy augmentation systems. Reports will be generated to disseminate the knowledge gained to the community.

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