Building Enhanced Resilience into Aviation

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ABSTRACT

The aviation sector is a very complex but generally successful enterprise within the United States. Unfortunately, over multiple decades a series of demonstrable major aviation disruptions have occurred, for a wide-ranging set of reasons. Thus, it is more than timely to consider how to enhance the resilience of the aviation sector. This will entail developing research projects that promote system-of-systems engineering solutions that focus on both vehicle design advances and novel airspace system architectures. Several such potential research initiatives are outlined in this paper.

NOMENCLATURE

A	Rotor disk area, ft^2; $A=\pi R^2$
A_P	Stopped-cycloidal-rotor projected area, ft^2
CTOL	Conventional takeoff and landing
c_R	Mean chord of rotors, ft
c_w	Mean chord of the fixed wing of aircraft, ft
C_P	Rotor, or proprotor, or fan power coefficient, nondim.; $C_P = P/\rho A V_{tip}^3$
C_P^*	Stopped-cycloidal-rotor power coefficient, nondim.; $C_P^* = P_{Total}/\rho A_P V_{blade}^3$
C_T	Rotor, or proprotor, or fan thrust coefficient, nondim.; $C_T = T/\rho A V_{tip}^2$
C_T^*	Stopped-cycloidal-rotor thrust coefficient, nondim.; $C_T^* = T_{Total}/\rho A_P V_{blade}^2$
DOF	Degree-of-freedom, nondim.
i_N	Nacelle tilt, Deg.
i_P	Nacelle pivot, Deg.
L/D	Lift to drag ratio, nondim.
L/D_e	Effective lift to drag ratio for rotorcraft, $L/D_e = WV/P$
P	Vehicle total power,
PAX	Number of passengers, nondim.
RIA	Runway independent aircraft
R	Rotor radius, ft
SOA	State of the art
STOL	Short takeoff and landing
S	(Fixed-) wing planform area, ft^2
V	Cruise velocity, ft/s (m/s)
VTOL	Vertical takeoff and landing
W	Takeoff gross weight of vehicle, lb$_f$
α	Angle of attack, Deg.
$\Delta D_e/L$	Delta effective drag to lift ratio, nondim.

INTRODUCTION

The aviation sector is a very complex but generally successful enterprise within the United States. It spans a spectrum of stakeholders that range from: the traveling public, to aircraft researchers and developers, to airport operators, to airlines and other aircraft operators, to the public/government

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regulators and officials. Overall, the aviation sector is critical to the smooth operation of society. After a series of demonstrable major disruptions to aviation over multiple decades, it is appropriate to consider how to enhance the overall resilience of the aviation sector. This will entail developing research programs that promote system-of-systems engineering solutions that focus on vehicle design advances and novel airspace system architectures. Several such potential research initiatives will be outlined in this paper.

BACKGROUND

Since the Oil Crisis of the 1970's, aviation has seen several major disruptions. These disruptions include the 2001 9/11 terrorist attacks, the 2008 recession, the 2020-2021 coronavirus pandemic, and emerging impacts from climate change. It is appropriate to consider both from a vehicle and an airspace system/networks perspective how to build additional 'resilience' into the aviation sector.

To accomplish this goal, it is necessary to consider engineering solutions to make the aviation sector more resilient to anticipated and potential future crises. To help define those solutions it is important to consider the following questions:

1. How can the aviation fleet be quickly 'right sized' and/or re-configured to meet the challenges of rapid changes in the economic operational environment?
2. How can aviation be refined to improve economic opportunities for urban and rural/regional communities in the US?
3. How can aviation respond to changes stemming from environmental challenges, including climate change?
4. How can aviation evolve to respond to the ever-increasing challenges of disaster relief and emergency response?

PRELIMINARY DISCUSSION OF PROBLEM

The following are some foundational principles that can aid in addressing the above questions:

I. Vertical lift (and short takeoff and landing (STOL)) aerial vehicles, particularly those having hybrid-electric propulsion, have the potential to expand into and fill several subsectors of the aviation sector, Ref. 1.

II. Autonomous systems and robotics technology also potentially have a profound influence on aviation.

III. Aviation can and must expand to new markets and to new applications to meet critical society needs. This, in turn, will economically sustain aviation during difficult times.

IV. Modular and distributed vehicles and/or subsystems could radically change aircraft design and operations.

V. Wholly new types of amphibious and multimodal vehicles and networks also have an opportunity to transform urban and regional aviation markets.

VI. A broad spectrum of vehicle sizes and capabilities will be required for building aviation resilience (e.g., disaster relief and emergency response, Ref. 2).

These foundational principles and their implications for addressing the question of building enhanced resilience into the aviation system will be discussed. Figures 1-2 are some examples of how runway independent aircraft (VTOL, VSTOL, and STOL aircraft) will be a vital component of that proposed enhanced resilience.

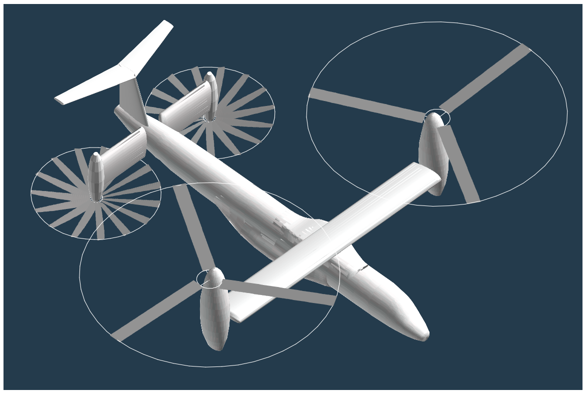


Figure 1. (VTOL, STOL, and V/STOL) Runway Independent Aircraft (RIA) to build enhanced aviation resiliency (Ref. 1, 3-4)

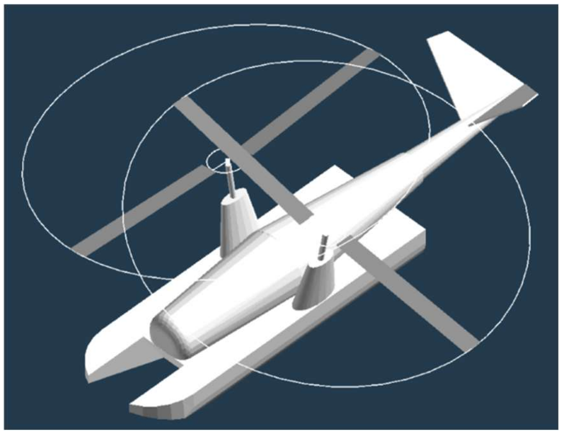


Figure 2. An emerging possible role for amphibious rotorcraft/aircraft (Ref. 5)

Figure 3 illustrates a possible new generation of STOL or V/STOL aircraft to maximize mission flexibility by being able to operate from vertiports, (short or long runway) airports, and even operate amphibiously. It emphasizes the use of distributed, and heterogenous rotors, and tilts the wings and rotor nacelles independently to enable this V/STOL flexibility.

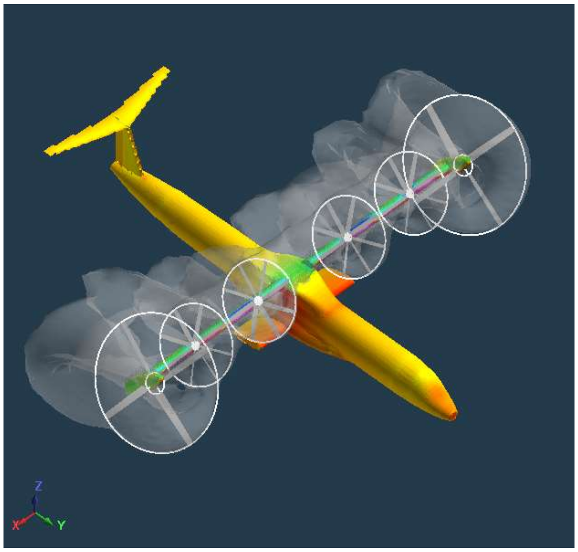


Figure 3. Hybrid tiltwing/tiltrotor aircraft with heterogeneous rotors and propellers for flexible V/STOL operation

The remaining portion of this paper will be divided into two parts. The first part of the paper will consider *system-of-systems architecture issues* related to developing new airspace and aerial transport systems for the future. The second part of the paper will examine *vehicle design considerations* for new classes of vehicles that might respond to making the aviation system of the future more resilient. Some novel or speculative/exotic (fixed- and rotary-wing) aircraft configurations are introduced. Finally, there is an appendix at the end of the paper that summarizes some initial design requirements and vehicle sizing considerations for potential amphibious V/STOL aircraft that might be responsive to adapting to future climate change impacts as well as overall trying to enable sustainable, green aviation for regional commercial rotorcraft.

SYSTEM-OF-SYSTEMS AIRSPACE/AERIAL TRANSPORT ARCHITECTURE OPPORTUNITIES

Airspace resilience must be provided for: (1) short-term or transient unexpected events, (2) moderate-duration single-occurrence acute, or periodic chronic occurrences, that may or may not be anticipable and (3) long-term, progressive trends related to technological, environmental, or socioeconomic changes. Engineering solutions for resilience for airspace systems that fall within each of these three categories of problems will present unique challenges. These solutions will be engineered into existing or future systems.

Airspace Flexibility to Respond

An example of airspace flexibility is the ability to accommodate self-organizing emergency networks using vertical lift aerial vehicles. One early study into this type of emergency VTOL networks is Ref. 2. This issue of repurposing or commandeering urban air mobility vehicles during emergencies was also touched upon in Ref. 6; this is analogous to purposing public transit buses to support hurricane evacuations. Accordingly, the development of novel aerial transportation networks should seek to balance out commercial transport interests and potential public service interest (utility) of such potential dual-purpose vehicles. Reference 7 discusses this opportunity for dual-purpose aerial vehicles in the context of 'delivery drones' being pressed into public service disaster relief and emergency response (DRER) efforts, i.e., instead of delivering online shopping purchases, if an emergency occurs, the same drones could be delivering small packages of food aid or first-aid medical supplies.

Optimizing for Multimodal Mobility Systems

A few rotorcraft aerial transport network concepts have been, and are being, explored at NASA Ames. These include 'Skimmer,' 'New Nomads,' 'Pogo,' and 'Unity' networks. Each aerial transportation network concept seeks to introduce some novel mission capability to urban and regional aerial transport of people and goods.

'Skimmer' networks are networks for amphibious VTOL aerial vehicles (e.g., Fig. 2). Refer to Ref. 5 for more details. As interest in urban aerial mobility grows, it is worthwhile to consider whether amphibious vertical takeoff and landing vehicles can play an important role in providing such mobility.

'New Nomads' networks are about integrating ground mobility with aerial mobility with transport of not just passengers but work- and living-space 'habitats' modules, Ref. 8 (Fig. 4). Such habitat modules could be transported by autonomous tugs on roadways and/or transported by 'skycrane' like VTOL platforms. This would potentially address not only traffic congestion but other critical urban planning challenges, such as providing for adequate cost-effective housing and reduced office-space infrastructure to promote economic growth.

Figure 4. New Nomad short-range multirotor configuration (Ref. 8)

‘Pogo’ networks are a hybrid-electric VTOL/VSTOL vehicles analog to bus and rail networks (Fig. 5). For example, a linear network of vertiport charging stations for hybrid VTOL/VSTOL vehicles could potentially be overlayed with respect to existing rail stations and freeway rest stops. This would balance vehicle per-charge range with a modest number of large rail-station-like vertiports/charging stations. Developing regional CTOL electric-propulsion vehicles is worthy of research but, likely, such longer-range CTOL vehicles will be hybrid-electric in nature. This will reduce their carbon-footprint by some modest amount but will not have the payoff of all-electric vehicles. The only way to have longer-range all-electric vehicles is to string together pogo-like hops (a series of short-haul flights) with moderately frequent recharging and/or swapping of vehicles.

Figure 5. Notional Pogo Network Vehicle (AI-generated image using Microsoft Copilot); railway-like regional air mobility

Figure 6 is another possible notional vehicle tilting ducted fan configuration (see Refs. 9-10) that might be responsive to the Pogo network concept. Unlike the more conventional ducted fan aerial vehicle portrayed in the Fig. 5 artwork, the Fig. 6 tilting ducted fan vehicle employs oval ducts and embedded tandem fans/rotors to provide a simple flight control approach that is partly inspired by quadrotor drone flight control in hover and low speed, helicopter-mode, edgewise forward flight.

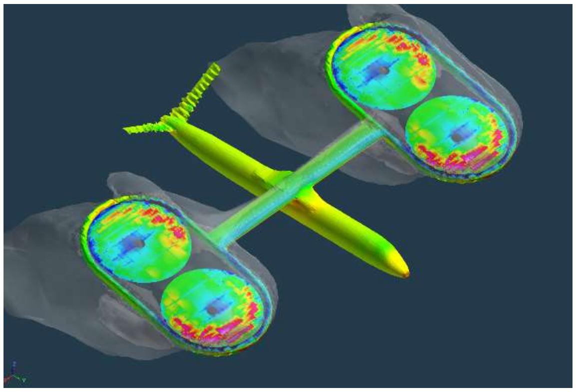
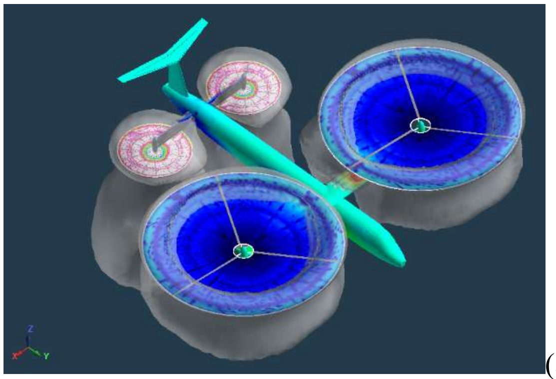
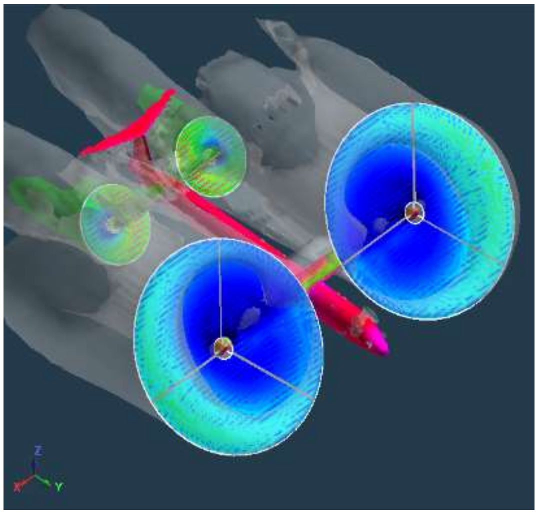


Figure 6. Another tilting ducted fan aerial vehicle (depicting early transition/conversion)

Several possible hybrid-electric tiltwing, tilt-duct, tiltrotor vehicles (e.g., Refs. 1, 9-10) could potentially support regional air mobility with eVTOL or eSTOL requirements. Mid-fidelity CFD predictions of another notional, potential Pogo network vehicle (based off the 'Flex Type-A' concept noted in Ref. 1) is shown in Fig. 7a-d.


(a)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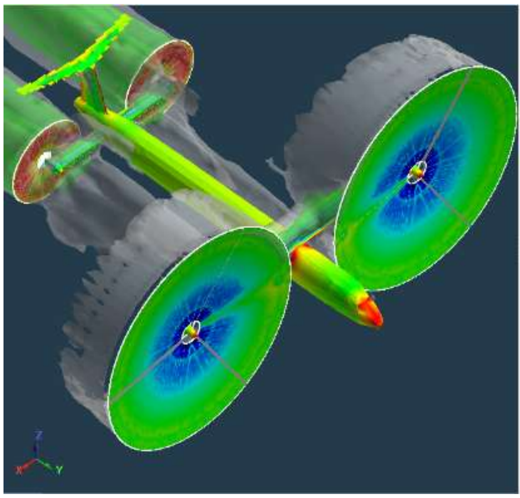
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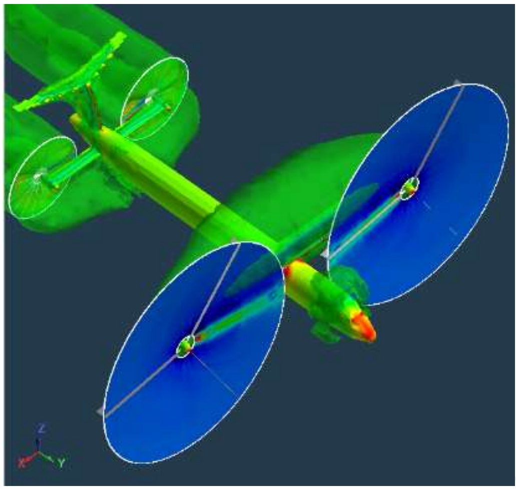
(d)

Figure 7. CFD of a Pogo network vehicle concept: (a) hover, (b) transition or conversion, (c) early cruise, and (d) late cruise

'Unity' networks are aerial vehicle networks that link local or rural communities with urban centers (Fig. 8). Such networks, through a combination of CTOL, VSTOL, and VTOL electric-propulsion vehicles encompassing moderate-sized passenger-carrying or cargo-carrying vehicles and small aerial robots, would increase regional economic strength as well as improve connectivity with nearby urban centers. An example of the criticality of this need is emergency hospital services for rural communities that no longer have local hospitals.

Figure 8. Notional Unity Network Vehicle (AI-generated image using Microsoft Copilot)

Mid-fidelity CFD predictions of a Unity network vehicle is shown in Fig. 9a-b; predictions performed with the RotCFD software tool, Ref. 23. Multirotor vehicle configurations, with or without ducts surrounding the rotors, have become quite popular with respect to the urban air mobility (UAM) developer community. UAM vehicles with modest design adjustments might make good candidate vehicles for Unity networks.

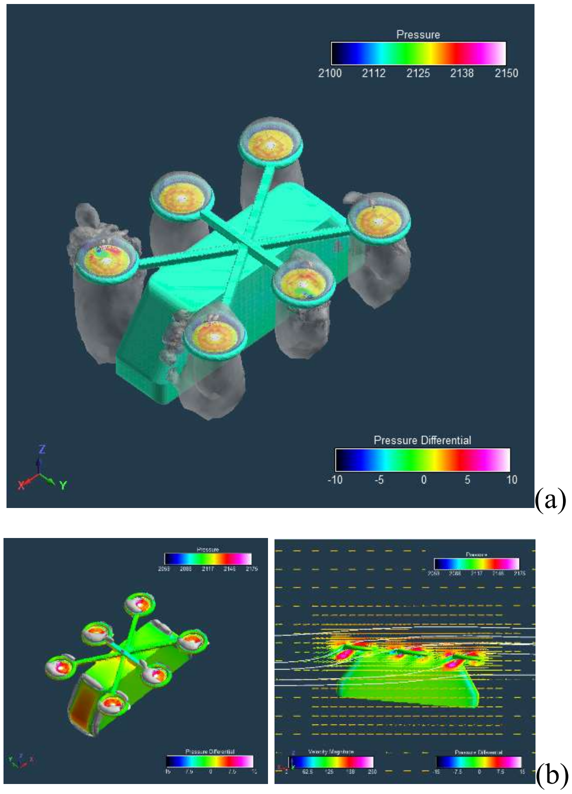

Figure 9. Mid-fidelity CFD (isosurfaces of velocity magnitude, body surface pressures, and rotor disk differential pressures) of a Unity network vehicle concept: (a) hover and (b) forward flight

Sustainable/green aviation will only be fully realizable if both the vehicle design <u>and</u> the system-of-systems network architecture are considered in a combined holistic manner. Figure 10 illustrates a notional integrated set of Pogo (regional) and Unity (local) networks along the US west coast. This continues the analogy of railway networks in the conceptualization and study of the Pogo and Unity networks.

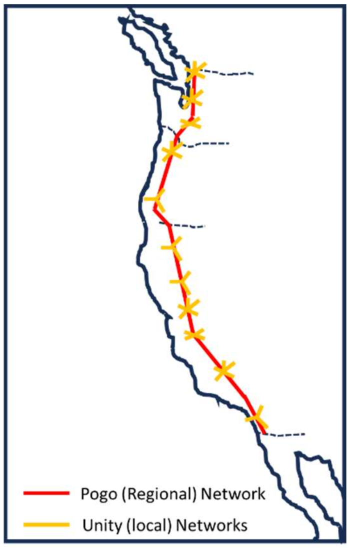

Figure 10. Unity and Pogo Networks integrated together in a notional west coast system

Vertiports (Large and Small) Everywhere

Vertiports for large and modest-sized aircraft for passenger/cargo-carrying are currently being discussed in detail by researchers. Smaller neighborhood vertiports, automated 'sentinel stations,' and even kiosk-type vertiports have not been fully considered. Some examples of limited work in this area are Refs. 7 and 11. Future research needs to focus more on this area of investigation.

This issue regarding the potential introduction of many vertiports – both large passenger-carrying vehicles (Fig. 11) and smaller 'drones' – is an important consideration in attempting to build in enhance resilience into the aviation system of the future.

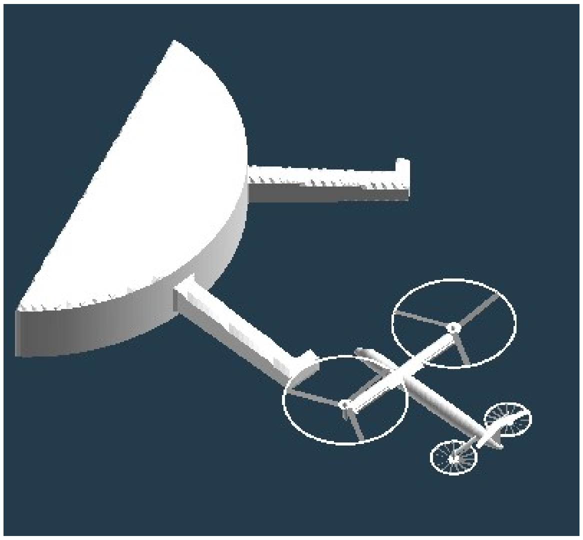

Figure 11. Large vertiports for passenger-carrying rotorcraft at airports

Merging/Evolving UTM and UAM and Radically Transforming Air Traffic Control

This paper suggests several research opportunities that, if pursued, will necessitate a radical transformation of current UAV Traffic Management (UTM), urban air mobility (UAM), and air traffic control (ATC) concepts or architectures. Some near-term research opportunities that are primarily focused on the intersections of vehicle and airspace research are outlined below:

1. Taking a vehicle sizing tool like NDARC (Ref. 12) and exporting out input files for NASA airspace analysis tools like FACET (Ref. 13), etc.

2. Taking ANOPP (Ref. 14) acoustic results and developing unique low-noise flight trajectories for novel aircraft configurations that could be fed into airspace tools.

3. Using airspace tools to what-if novel flight trajectories that then could be used to specify mission/design requirements for

sizing tools like NDARC or flight control handling-quality tools like FlightCODE (See Ref. 15).

4. Taking results from FlightCODE to define emergency maneuvers and/or contingency flight paths that then could be factored or incorporated into airspace simulations.

Vehicle-centric and airspace-centric analysis tools currently require a great deal of manual effort to exchange/share results with each other – especially for novel aircraft and/or rotorcraft. To improve and/or automate the process for information exchange between analysis tools could be a critical modeling and simulation need for the future. The above list of analysis tools and the opportunities for exchange or sharing of results is only a partial summary of the overall analysis needs. Relevant parsing tools may also need to be developed for efficient transfer of data between the various analysis tools.

Aerial Robotic Ecosystems

It is possible in the far future that aerial (or hybrid aerial/ground/water) robots will come to number almost as many as birds in the sky thereby resulting in large aerial robotic ecosystems, aka 'mech life.' Clearly centralized control of such aerial robotic ecosystems will not be feasible. Further, this aerial robotic ecosystem is going to have to safely coexist with more conventional aerial vehicles and conventional airspace management systems and strategies.

This additional issue regarding the potential introduction of whole 'aerial robotic ecosystems' that must nonintrusive interact with and or cooperate with passenger-carry aircraft is yet another example of a huge potential leap in aviation system complexity that might occur in the mid- to far-term future. One example of such an 'aerial robotic ecosystem' is the forest replanting aerial robots of Ref. 16. The nascent ideas of Ref. 16 have now become mainstream with the introduction of aerial robots performing actual forestry services, Ref. 17.

VEHICLE DESIGN OPPORTUNITIES

There is clearly a role for advanced aerial vehicle design in building in enhanced resilience into our aviation system. A few ideas for addressing such enhanced resilience via aircraft design (and the associated system-of-systems architectures employing such vehicles) will now be presented. It is important to note though that the presented ideas are to inspiration other researchers and developers to propose their own ideas.

Expanding Vertical Lift Aerial Vehicles into all Aviation Sectors

Work throughout the mid-1990's to the late-2000's showed the potential for civil tiltrotor aircraft to meet short haul and regional commercial aircraft markets (e.g., Refs. 3-4). The potential was also studied and demonstrated for tiltrotor aircraft to satisfy humanitarian relief and disaster relief and emergency response missions (e.g., Ref. 2). These studies somewhat fell to the sidelines, but the results are still just as valid today as much as they were in the past.

Enabling Modular and/or Distributed Aircraft

Advanced structural design and manufacturing concepts, particularly for composite structures, coupled with advanced flight computer and controls and possible propulsion electrification (all- or hybrid-electric), could enable more flexible airframe/vehicle configurations.

Monohull airframes could use swappable ‘plugs’ in the fuselage to reduce cabin size and passenger loads, while still being aerodynamically tailored, respectively, to be low drag in both configurations. These swappable plugs should be enabled such that very little retrofitting/remanufacturing is required; ideally this could be accomplished almost on-demand. Twin hull CTOL aircraft have in the past been examined before by NASA. But this was primarily from a fuel efficiency perspective and not from a ‘resilience’ perspective. Twin hull tiltrotor aircraft have also been briefly studied, Ref. 1. Swappable wing extensions should also be studied in the context of resilience engineering.

Monohull airframes could be replaced by shorter fineness-ratios multiple hulls that could be mated at multiple attach points on the primary wing. These multiple hulls could be staggered spanwise (with the respect to the primary wing) or even staggered vertically in a closely packed geometric arrangement. Hulls could be removed or added to increase cabin space and passenger loads on-demand. Two twin hull tiltrotor configurations were initially examined in Ref. 1. Figure 12 illustrates yet another twin hull tiltrotor conceptual design approach.[2]

Figure 12. One possible twin hull tiltrotor configuration (artwork AI-generated by Microsoft Copilot)

One way of ‘right-sizing’ aircraft is to form large aircraft from multiple small aircraft using various ‘parasite’ aircraft ensembles; for example, see Ref. 24. Parasite aircraft formations can be formed with individual aircraft with swept or un-swept wings or, alternatively, small aircraft with oblique or scissor (pivoting) wings. Such parasite aircraft ensembles could be applied to both fixed-wing (CTOL) and rotary-wing (VTOL) vehicles. Closely spaced rotors or proprotors can also potentially be accommodated in parasite aircraft ensembles by using inter-meshing rotors.

Refer to Fig. 13 for a modular high-speed rotorcraft with tilting rotors. Previous work has studied modular rotorcraft (multirotor configurations with non-tilting rotors in edgewise flight). This, however, is the first presentation of a modular rotorcraft with tilting rotors. Each individual rotorcraft

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[2] This figure includes one of a few AI-generated images in this paper. AI images proved to be useful for early conceptualization or ideation but did suffer from image artifacts that ideally require manual artwork editing to improve the images. Such artwork editing was not performed for this paper to show the reader some of the artwork artifacts/defects that might occur with the current generation of software, including extraneous rotor/propellers being included in the artwork as well as extraneous wings, tail surfaces, and landing gear. On the other hand, some of the graphic art details (backgrounds, cabin interiors, etc.) were compelling from a first-order perspective.

element must be attached at the other rotorcraft (tiltrotor aircraft) wingtips with some level of structural/mechanical fixation and rigidity. The key limitation of this type of modular tilting rotor configuration is that the individual rotorcraft elements are limited to linear arrays in forming the aggregate or ensemble whole versus the two-dimensional matrix aggregates that can be formed with modular multirotor configurations.

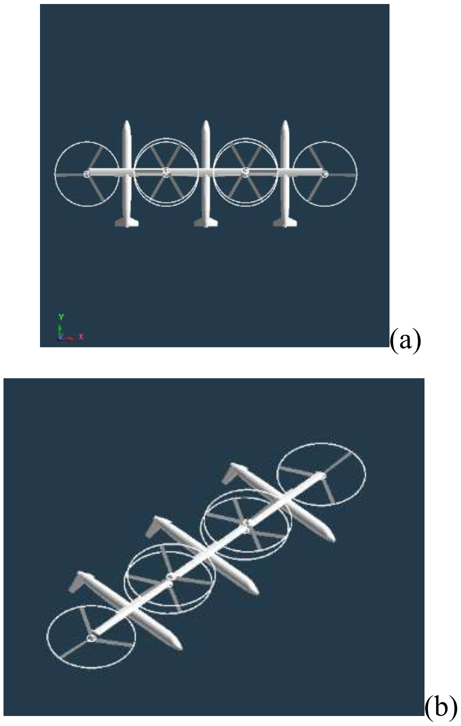


Figure 13. Modular high-speed rotorcraft – three elements, in an array, comprising the rotorcraft (in hover configuration): (a) planform view and (b) isometric view

Figure 14 is a five-element modular rotorcraft array. Each rotorcraft element has a pair of side-by-side tractor, or a pusher, type tilting rotors. This is very evocative of World War II wingtip-mounted 'parasite flier' aircraft concepts, though adapted to rotorcraft or tiltrotor aircraft versus conventional aircraft.

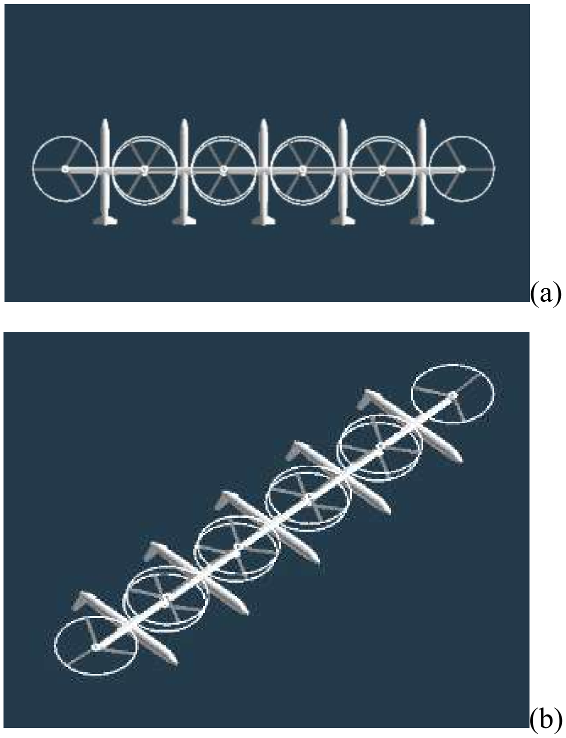


Figure 14. Modular high-speed rotorcraft – five elements, in an array, comprising the rotorcraft (in hover configuration): (a) planform view and (b) isometric view

These modular tilting rotor configurations could be assembled on the factory floor as a semi-permanent configuration or, even more ambitiously, assembled on the flight line to meet the needs of each individual flight.

Figure 15 presents some initial mid-fidelity CFD predictions for the three-element modular high-speed rotorcraft illustrated in Fig. 13 for hover, transition, and cruise conditions. Wing and fuselage surface pressures are shown; additionally, isosurfaces of velocity magnitude are also shown to highlight the rotor wakes in hover, transition, and cruise.

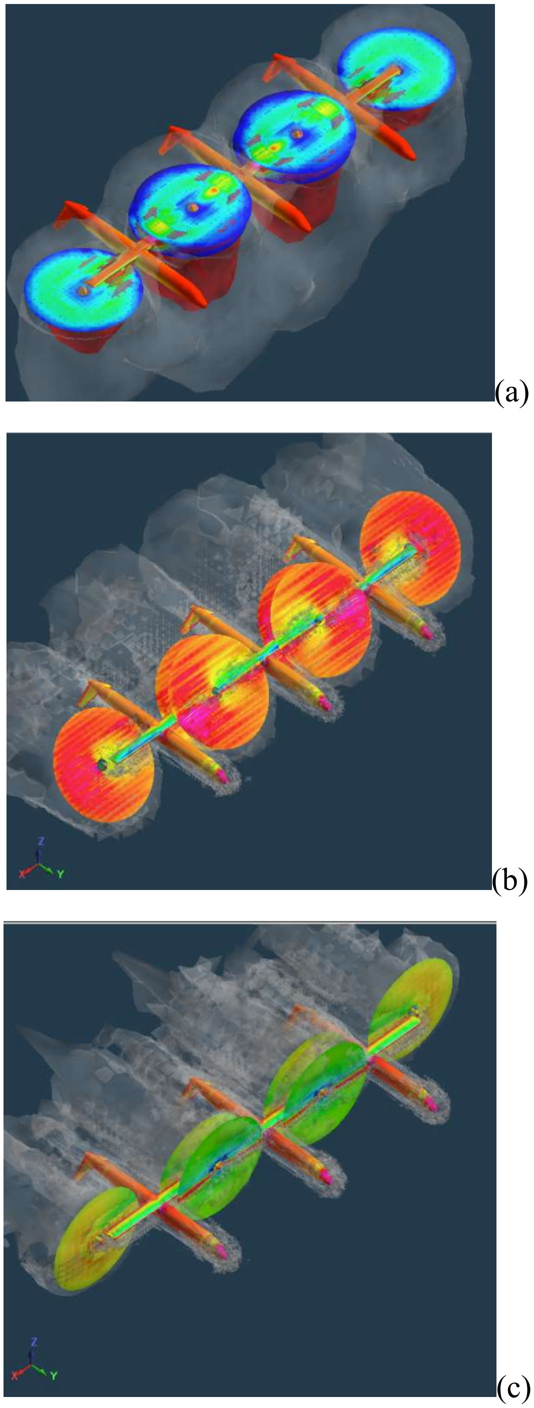
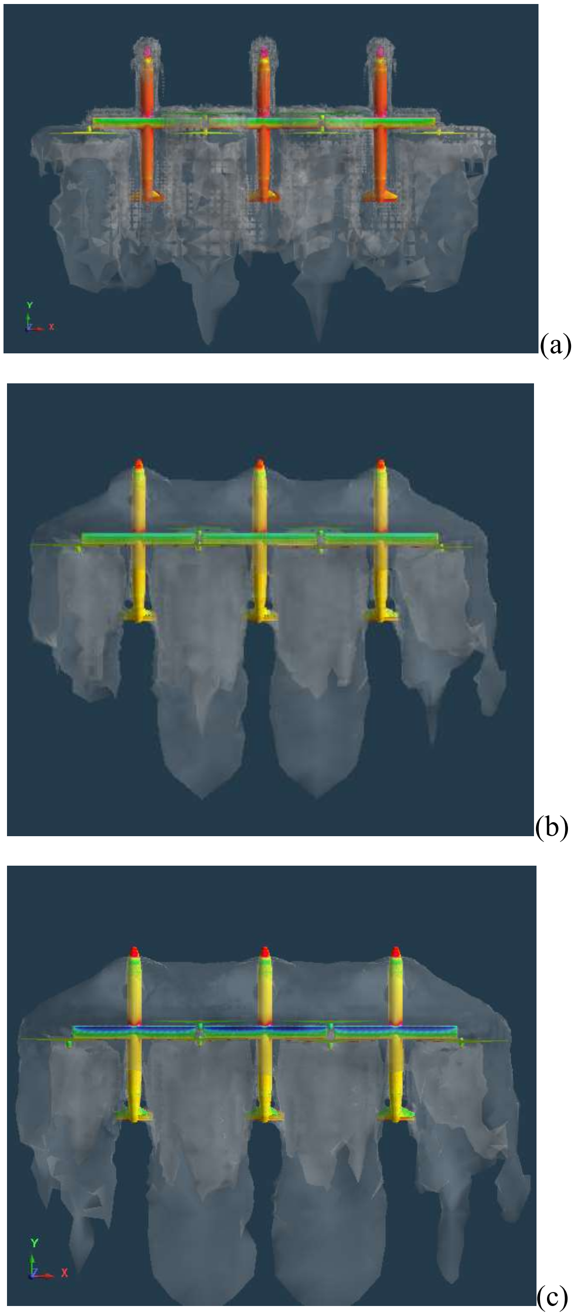
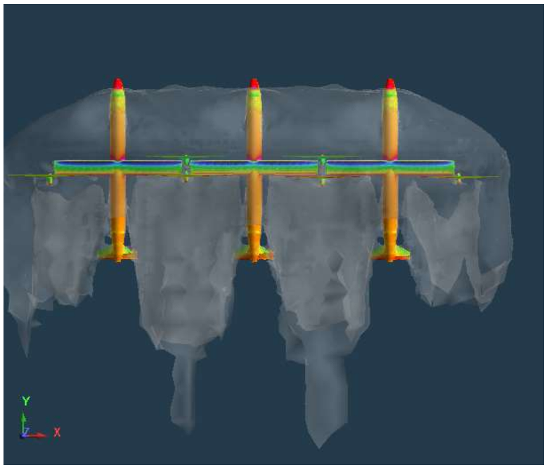


Figure 15. Modular high-speed rotorcraft – three elements, in an array, comprising the rotorcraft: (a) hover, (b) transition, and (c) cruise

Figure 16a-d presents planform views of the three-element tilting modular rotorcraft configuration for an angle of attack sweep. The wing upper surface pressures are shown as well as rotor wake velocity magnitude isosurfaces in cruise.

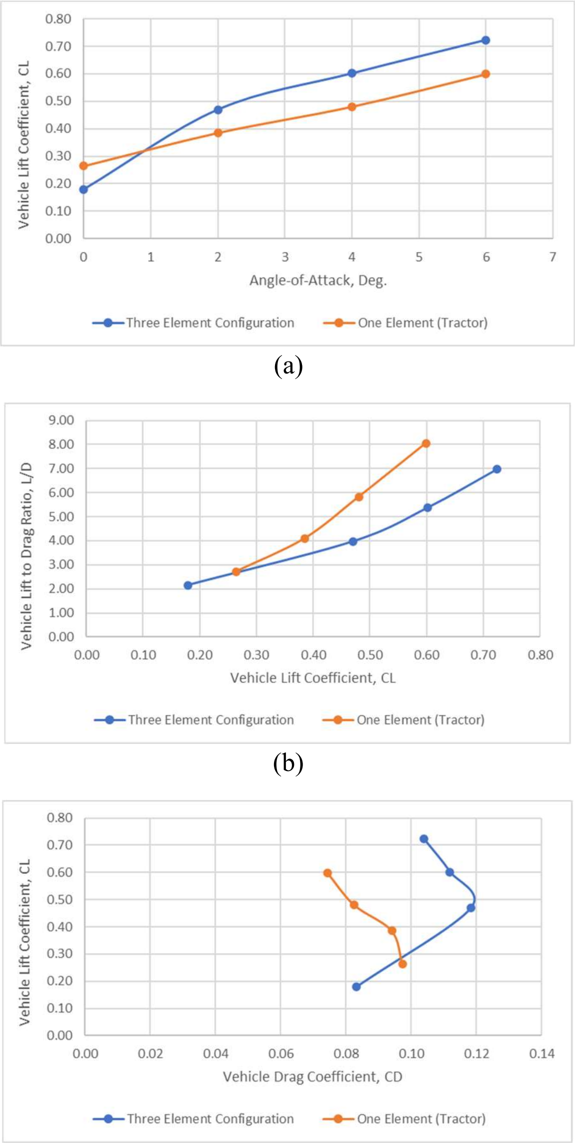




(d)

Figure 16. Modular tilting rotor (three-element) aircraft configuration initial mid-fidelity CFD predictions for an angle-of-attack sweep in cruise: (a) AOA=0 Deg., (b) AOA =2 Deg., (c) AOA=4 Deg., (d) AOA=6 Deg.

Figure 17a-c presents an illustrative set of mid-fidelity CFD predictions that considers '…the sum of its parts' question[3] for modular rotorcraft, in this case modular tilting rotor aircraft in linear arrays/arrangements, e.g., Figs. 13-14. The anticipated increase in lift efficiency because of the aggregate increase in wingspan is clearly seen in Fig. 17a. However, there does appear to be an increase in net parasite drag due to the complexity of the geometry at the wing tips of some of the vehicle elements; this complexity results from aerodynamic interference effects stemming from some wing tips effectively having two nacelles (one for a tractor proprotor and one for a pusher proprotor) mounted (in proximity) to them. Future work will have to examine how to reduce net parasite drag for any modular tilting rotor (aggregate/ensemble) configuration. This increase in parasite drag with the three element vehicle configuration is why its lift-to-drag ratio is less than that of the one element (tractor) configuration.



(a)

(b)

(c)

Figure 17. Mid-fidelity CFD predictions of aggregate modular tilting rotor aircraft: (a) CL versus AOA, (b) L/D versus C_L and (c) C_L versus C_D

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[3] The complete quote is attributed to Aristotle: "The whole is greater than the sum of its parts."

Exotic Modular Conventional Takeoff and Landing (CTOL) Aircraft

In the late nineties, exotic nonlinear lifting surface CTOL aircraft were being considered to address future aviation, Ref. 18. Figure 18 is concept artwork to introduce a novel 'skytrain'[4] vehicle that could use ring-wings or elliptical/oval-wings as compact lifting surfaces. Ring-wings and elliptical/oval-wings do not completely eliminate trailed tip vortices but, perhaps, reduce their strength. Accordingly, it is possible that optimized ensembles of ring or oval wings might reduce the net magnitude of induced velocities from one set of elliptical/oval-wings on another subsequent downstream set of wings.

Figure 18. 'Skytrain" CTOL ring-wing vehicles (AI-generated image by Microsoft Copilot)

Figure 19 is an isometric view of a CAD/CFD model for the skytrain CTOL concept. Instead of using ring wings, a pair of tandem oval wings is employed for each modular 'car' of the skytrain ensemble or aggregate. It is initially assumed in this early modeling that some amount of kinematic and/or aeroelastic degrees-of-freedom (one DOF as shown, i.e., a lateral back and forth 'wagging') is allowed between 'cars' but this is purely notional at this point. The lead car has a singular cabin like element added to its front for streamlining and reduction of drag. The trailing car has a 'caboose' like tail added to it, again for streaming and reduction of drag. The 'joints' between cars is again purely notional (again to be evocative of train-like inter-car connections); clearly the geometry/transition of these 'joints' between cars would be critical to keep overall skytrain drag to a minimum. The use of ring wings, or elliptical wings, or oval wings (as in this CAD/CFD model) is intended to reduce trailed vorticity (and induced angular velocities) to a minimum to minimize wing-to-wing aerodynamic interference effects. The oval wings being shown in Fig. 19 (and the ring wings in Fig. 18) are of a constant chord all along the perimeter or circumference of the wings. This is not likely optimal. It is more likely, and something appropriate for future study, to consider tapering the oval or elliptical wings in the vicinity of the more circular arcs of the wings (i.e., at their 'tips'). The whole oval wing versus elliptical wing – and intermediate wing design space – is a very interesting topic for future study. Finally, the fineness ratio of the oval/elliptical wings should be explored; one extreme is a ring wing and the other extreme is a purely planar biplane with edge-plates configuration). Finally, each 'car' has

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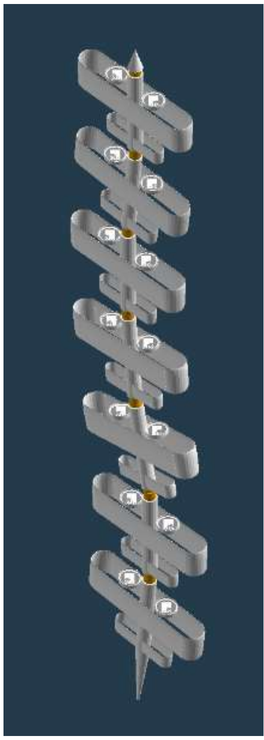
[4] The notional skytrain CTOL concept presented is not referring to the Vancouver, BC, 'SkyTrain' metro railway, or the Phoenix airport 'Sky Train' metro, or even the C-47A "Skytrain" WWII paratrooper carrier aircraft (which was also used to tow gliders in combat).

its own twin pair of ducted fan propulsors, or turbofan engines, nested in between the leading oval wing of the car.

The initial work in this paper, that of the aerodynamics of oval wings, somewhat indirectly follows previous work in Refs. 9-10 that studied oval ducts for tilting ducted fan VTOL aircraft.

The purpose of discussing such an exotic, speculative aircraft configuration (as was done for the modular tilting rotor vehicles of Figs. 13-14) is as an attempt to promote 'out-of-the-box' thinking and not necessarily an advocacy for one or more vehicle concept. But more than anything, both vehicle concepts seek to address in principle the assertion of this paper that resiliency in the future aviation system will be tied to the overarching theme of rightsizing aircraft for markets demands through use of some level of vehicle modularity.


(a)

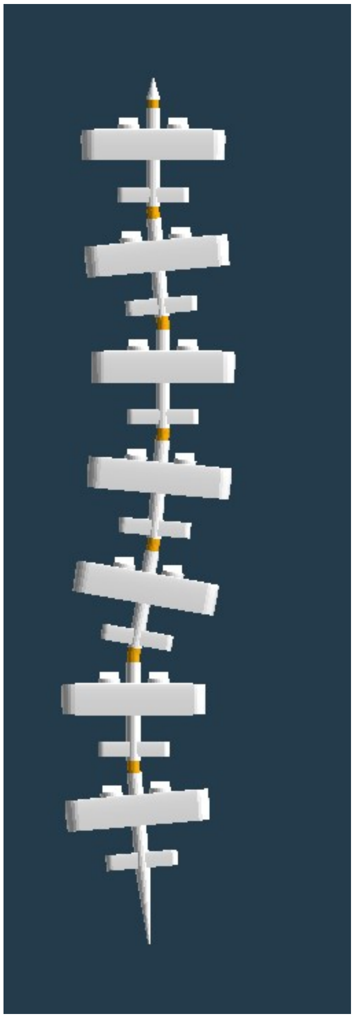

(b)

Figure 19. Skytrain (modular CTOL vehicle concept): (a) isometric view and (b) planform view

Figure 20a-b presents some mid-fidelity CFD results for the skytrain notional configuration shown in Fig. 19 for a one and two car configuration at zero angle-of-attack. A three car configuration is shown in Fig. 21a.

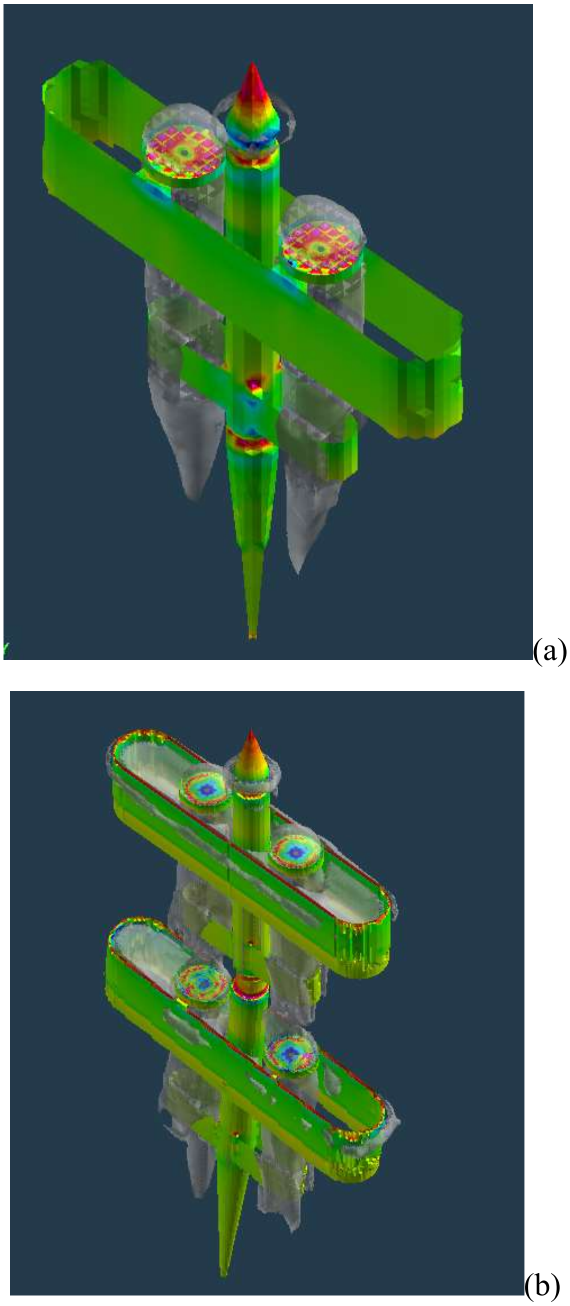


Figure 20. Mid-fidelity CFD (isosurfaces of velocity magnitude, body surface pressures, and rotor disk differential pressures) of a skytrain vehicle concept at AOA=0 Deg.: (a) one 'car' and (b) two car

Advances in magnetic levitation (maglev) rail systems are also making it possible to consider the use of maglev for aircraft takeoff and landing, e.g., Ref. 19. Use of maglev for skytrain vehicles might make for an interesting complementary or parallel study. If maglev does have some role to play as to aerial vehicle surface locomotion (taxiing and takeoff), then an even more speculative line of investigation might be to consider whether a skytrain configuration might also play a dual role in a multi-modal transportation system. The skytrain could be used in place of railway surface transport by elevated trains but instead by a skytrain on the ground being propelled by maglev until it gets to the airport where it could takeoff and fly on wings and turbofan engines.

Figure 21a-d presents some limited mid-fidelity CFD results for a three-car skytrain vehicle concept configuration. (CFD models with the mid-fidelity RotCFD software tool had difficulty with four or more skytrain cars; hopefully this won't pose a problem for future investigations.)

Figure 21a-d presents wing and fuselage surface pressures as well as isosurfaces of flow field velocity magnitude (allowing visualization of turbo-fan exhaust/wakes as well as the accelerating flow above the wing leading edges). The increasing leading-edge upper suction pressures (deeper blue hue with increased suction pressure) with angle of attack can be clearly seen in Fig. 21a-d. From such predictions the aerodynamic interference effects of one set of wings on other (downstream) wings can be assessed.

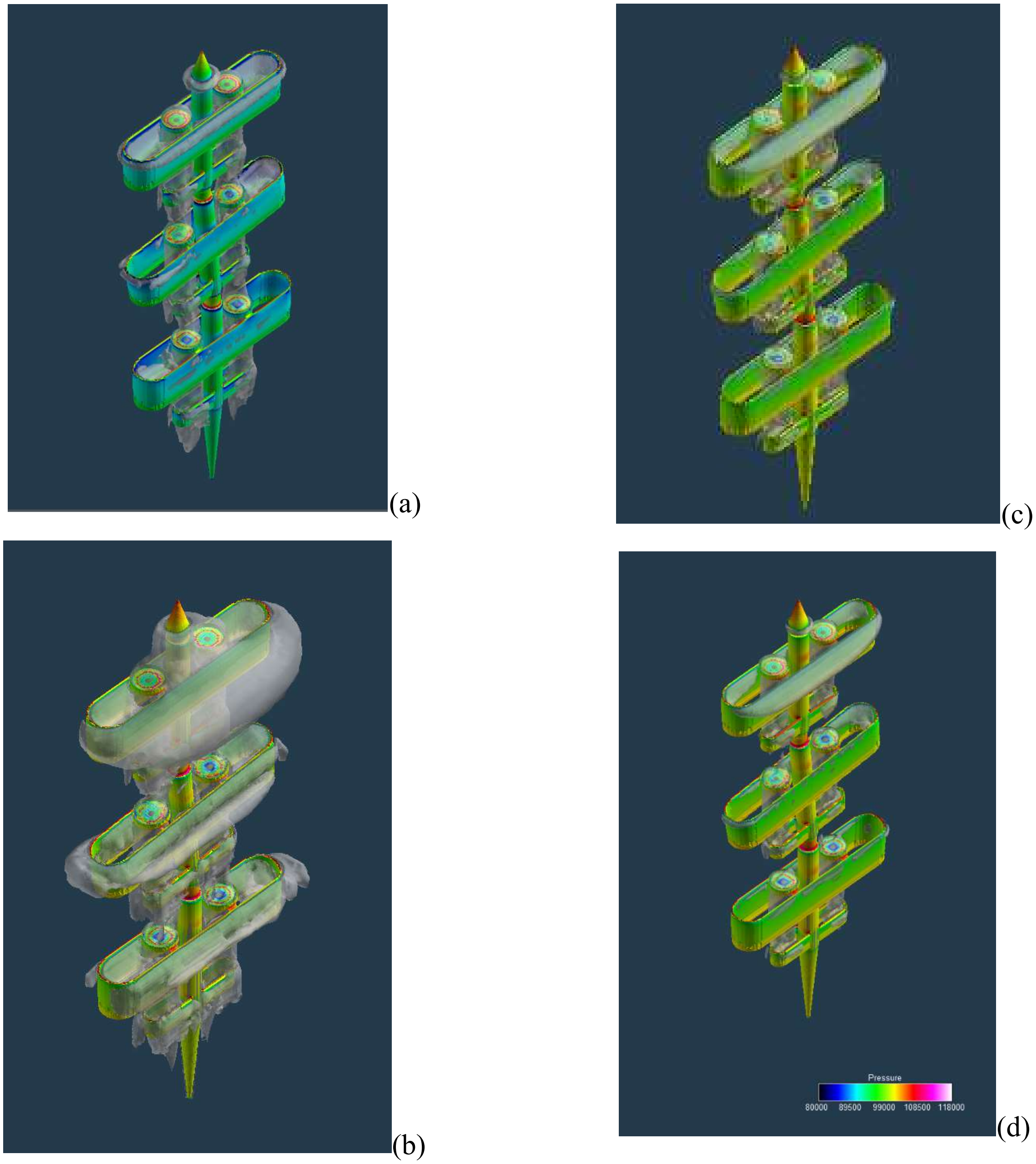
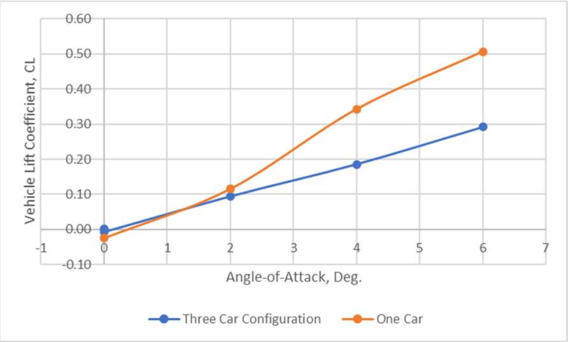
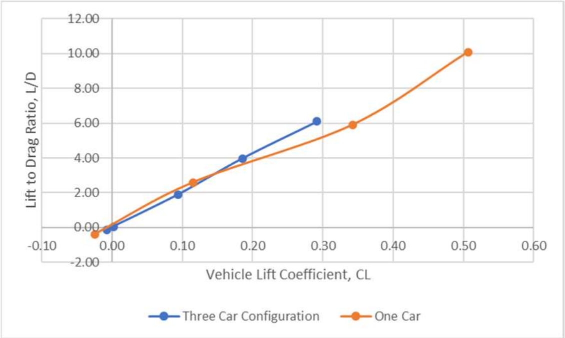


Figure 21. Mid-fidelity CFD (isosurfaces of velocity magnitude, body surface pressures, and rotor disk differential pressures) of a top/planform isometric view of skytrain three-car vehicle concept: (a) AOA=0 Deg., (b) AOA=2, (c) AOA=4 Deg., (d) AOA=6 Deg.

Figure 22a-c presents an illustrative set of initial predictions that considers '…the sum of its parts' question[5] for modular skytrain eCTOL or CTOL concept, e.g., Fig. 19. It is clear from the initial mid-fidelity CFD results that the use of the oval wings did not reduce the magnitude of the induced velocity aerodynamic interference effects of forward wings influencing the aft, downstream, wing as much as might be hoped. The lift curve slope of the three-car configuration is only about sixty percent of the one-car baseline. Part of the problem might lie in the gridding fidelity of the automated grid body fitting employed during this modeling; the gridding along the circumference of the 'oval' section of the wings is very coarse and needs to be further improved/refined. This is clearly an area of future aerodynamic investigation to make this exotic aircraft concept feasible.



(a)



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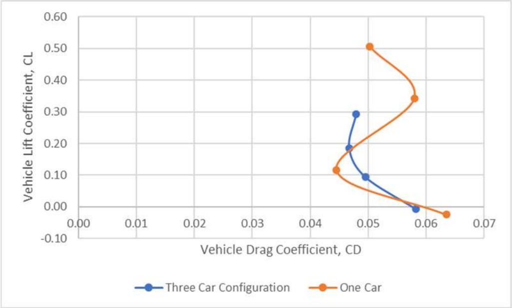

(c)

Figure 22. Mid-fidelity CFD predictions of aggregate modular skytrain concept: (a) CL versus AOA, (b) L/D versus CL and (c) CL versus CD

Providing 'Plug and Play' Propulsion Systems and Airframe Structures

Modularity of aircraft – especially with respect to propulsion system elements to quickly go from one mode of operation such as VTOL flights, to STOL flights, to CTOL flights – could be the key factor in the realization of sustainable aviation for rotorcraft and other runway independent aircraft.

With respect to propulsion system modularity, a turboshaft-driven electric generator 'pallet' could be swapped out with a large battery pack to quickly go from a hybrid-electric to an all-electric aircraft. If battery packs could be swiftly removed or installed on-the-ground between flights then a single V/STOL hybrid-electric runway independent aircraft could efficiently, sustainably fly on-demand VTOL, STOL, or CTOL flight profiles and, thereby, optimize its takeoff weight and overall flight performance efficiency for each individual flight.

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[5] The complete quote is attributed to Aristotle: "The whole is greater than the sum of its parts."

Further, from an overall vehicle design reconfigurability perspective, it should be feasible (and aspirational from an engineering perspective) to quickly exchange propulsion systems on a given airframe without substantial modifications: exchange a turbofan with pusher or tractor advanced propfans or even more radical to exchange these propulsion systems with rotary-wing side-by-side rotors (or tiltrotor proprotors) and gearbox/turboshaft engines. Or, alternatively, it should be theoretically feasible (and aspirational from an engineering perspective) to quickly exchange a CTOL 'cruise optimized' wing with a VTOL 'jump/takeoff optimized' wing for side-by-side or tiltrotor type rotorcraft configurations. See Ref. 20 for one example of a study investigating such design reconfigurability, or rather 'conversion' capability.

Transitioning from Urban Air Mobility to Regional Aerial Transportation Systems

The utility of urban air mobility would be greatly increased if the technology were extended to regional aerial systems, i.e., flights between neighboring cities. This might, in turn, increasingly justify examining hybrid-electric propulsion versus all-electric propulsion. It may, as well, require examining how to better incorporate multimodality mobility into the overall transportation system (e.g., networks comprised of amphibious vertical takeoff and landing aerial vehicles, Ref. 5).

Recent advancements within the urban air mobility sector have begun the transition from urban to regional markets, albeit with still relatively small, short-range, and slow aircraft. But incremental progress is still progress. Reference 21 recently announced the flight of a remotely piloted hybrid-electric VTOL aircraft (using hydrogen-based fuel cells) to over 500 miles (or over 800 km); this aircraft was a near-production nominally passenger-carrying UAM/eVTOL vehicle.

From the perspective of trying to preserve a sustained healthy research and development community, continuing to build the urban air mobility market while at the same time beginning to explore the regional market is a good thing. This paper asserts that large commercial passenger-carrying (PAX>50) hybrid-electric vehicles that can fly at least tiltrotor SOA speeds (>250knots or >130 m/s) and modest ranges (>500 miles or >800 km) should ultimately be the rotorcraft research community's goal for the future.

Embracing 'Electric Aircraft' and not just Electric Propulsion

NASA over decades has invested a substantial amount of research into active flow control and active aeroservoelastic actuators to enhance the aerodynamic performance and efficiency of aircraft as well as to flight dynamics and structural/vibratory load alleviation. However, active flow control techniques place significant demands on electric power – above and beyond that for providing for all- or hybrid-electric propulsion. Active rotor control servo-actuators also demand a considerable amount of electric power as well. The complexity of active flow control and aeroservoelastic actuators and the above noted added power demand have kept these well studied performance-enhancing systems from being implemented to-date on production aircraft.

Reference 6 made some of the first suggestions to the aerospace research community as to embracing the ‘electric rotorcraft’ concept instead of focusing solely on rotorcraft with electric propulsion. As noted in Ref. 6, if very large amounts of electric power storage or production is already going to be installed onboard an aircraft for enabling electric propulsion, then it is a relatively small conceptual leap to consider implementing active flow control and/or active surfaces/actuators that are also electrically powered. In that case, an ‘electric rotorcraft’ could theoretically become so much more than an aircraft with electric propulsion, however singularly important that is. Instead, the introduction of aircraft with large electric energy storage might enable introduction of a suite of long-researched technologies to promote increased aircraft efficiency and expanded operational envelopes.

Expanding Autonomous System Technology into all Aircraft Life-Cycle Phases

In a workforce context, people are costly. Economic downturns result in significant layoffs. Expanding automation and autonomous system technology into all life-cycle phases of aircraft would potentially moderate, over time, large swings in aviation workforce. However, such expansion of automation in aviation must emphasize safety and stability.

Most urban air mobility, aka eVTOL, developers are currently pursuing human piloted aircraft so as get FAA certified as quickly as possible. Only a few developers are currently seriously pursuing passenger-carrying autonomous aerial vehicles. Reference 6 devoted a portion of its discussion as to the system analysis and economics of passenger-carrying autonomous aerial vehicles for metropolitan aerial transportation systems. This preliminary analysis laid the groundwork for a more in-depth consideration of this research question in the future. In the context of building in enhanced resilience in aviation, the potential use of autonomous aerial vehicles for commercial passenger transport will require extensive community assessment over the next couple of decades.

Responding to Wholly New Aviation Markets

A considerable amount of innovation is currently underway within the rotorcraft community. Urban air mobility vehicles, aka eVTOL, are well on their way to certified production. Work also continues in a steady sense on ‘delivery drones.’ Several other transformative classes of vehicles and new mission are also being explored. The future of aviation needs to consider not just legacy/state-of-the-art aircraft and rotorcraft but must remain sufficiently adaptable to respond to new aerial vehicles and missions. Among some of these future aerial vehicles and missions are as follows: (a) HEROS, or novel crewed aerial vehicles and robotic aerial platforms for rapid response disaster relief and emergency response missions; (b) Good Stewards, or robotic aerial platforms for environmental monitoring and biodiversity or wildlife conservation; (c) “How to save the world, one life (and UAV) at a time!”, or use of autonomous aerial vehicles and aerial robots for disaster relief and emergency response; (d) the development of ‘mech life’ to monitor, conserve, and take remedial actions to sustain the billions of humans on the planet and the whole of its flora and fauna to achieve a sustainable world.

Such an expanded aviation system would be challenging if only one or two new application domains were emerging, but there is potentially a whole gamut of novel aerial vehicles and aerospace operational models and business cases being considered for the mid- to far-term future. Such potential increased complexity of the aviation system argues for improved system analysis and systems engineering tools.

FUTURE WORK

This paper is merely an introductory recommendation that the aerospace engineering community try partially redirecting some of its research efforts towards trying to enhance the resiliency of the aviation sector. As to the specifics of what that might entail, a short summary of concepts – ranging from vehicle-centric to air transportation system centric – is presented; to kick-start such rotorcraft research community discussion, a set of concepts to build in such resilience is also presented.

Ultimately future work in this area will also be performed, in parallel, to the complementary Climate-adjusted Air Transportation Systems (CATS) project (Ref. 22). CATS is funded by the NASA Convergent Aeronautics Solutions (CAS) project. CATS seeks to focus on building enhanced resilience into Aviation specifically in response to anticipated climate changes foreseen in the 2050 and beyond timeframe.

The appendix of this paper will touch upon some of the more aircraft design related aspects of the CATS project. This includes the sizing of a V/STOL vehicle (notional vehicle shown in Fig. 3) responding to aircraft design requirements that reflect anticipated climate impact effects.

CONCLUDING REMARKS

This work seeks to present a bold challenge for the aviation community: define new system-of-systems architectures to greatly enhance aviation resilience to adequately respond to a manifold set of potential disrupters, including the influence of climate change, economic downturns, energy crises, pandemics, and disasters of all types, etc. It is the broad assertion of this paper that vertical lift aerial vehicles will be a crucial factor in building future aviation resilience.

There is an opportunity to learn from the lessons from several decades of aviation disruptions. The future is largely unknown, but it seems reasonable to anticipate that future aviation disruptions will occur. It is time to take steps now to develop more resilient aerial vehicle design space and airspace systems.

The proposed research theme of building enhanced aviation resilience is highly relevant to the needs of the Nation, as well as a powerful unifying theme to focus and advance critical technologies for future vehicle design and airspace system development. This ‘resilience’ research theme can readily encompass some of the current NASA research portfolio and, therefore, represents not so much a radical change in direction but an expansive evolution.

In addition to the theme of building enhanced resilience in the aviation system, this work continues considering important questions related to sustainable, or ‘green,’ aviation. Because of the power intensive aspects of rotorcraft over conventional fixed-wing aircraft it is a challenging problem to consider how to implement ‘sustainable rotorcraft.’ It is the assertion of this study and similar earlier work, that it will be through a combination of both novel vehicle designs, new runway independent aircraft (which includes rotorcraft, VTOL, and STOL aircraft), compatible networks (of airports and vertiports), and new aviation operational business models (or use cases).

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APPENDIX – AIRCRAFT DESIGN PERSPECTIVE TO THE CLIMATE-ADJUSTED AIR TRANSPORTATION SYSTEMS PROJECT

The Climate-adjusted Air Transportation System (CATS) project is a recently initiated NASA Convergent Aeronautics Solutions (CAS) project 'Discovery' effort; see Ref. 12. CATS is envisioned as filling an important 'gap' in the current NASA

Aeronautics Research Mission Directorate (ARMD) research portfolio. Though ARMD and many other organizations are striving mightily to try reach carbon-neutral goals for the aviation sector by 2050, it is also becoming apparent that technological steps towards climate adjustment, or rather adaptation, should also be pursued by the aviation research community.

CATS is still in the very earliest of stages, but a substantial amount of literature review, problem scope definition, and high-level planning discussion has already occurred. The overall CATS effort will help lay the groundwork to debate and define a balance between climate mitigation and adaptation (for enhanced resilience).

A key element of the early efforts of the CATS effort is to do the tool development necessary to conduct robust data mining and data translation from NASA and other organizations climate model predictions to develop the inputs required for NASA ARMD airspace and aircraft analysis tools. One major point of consideration, it that it is currently unclear whether sea levels will rise in the 2050 or later time frame of a sufficient magnitude to require consideration of aviation system options such as building more airports on artificial islands and/or the use of amphibious aircraft as necessary steps to climate adaptation.

From an airspace operations and airport network perspective, a new type of airport network system (as distinguished from the current hub and spoke type networks) may need to be developed. Alternate airport networks might need to be proposed such as: decentralized or distributed networks; incorporating small airports and vertiports and VSTOL (aka Runway Independent Aircraft) into large airport networks; amphibious 'airfields' and amphibious aircraft integrated airport networks; and/or other multimodal network solutions. Such novel airport network concepts should be explored to increase airspace transportation system resilience in the 2050 and beyond time frame that adapts the airspace system to projected climate disruptions.

New types of aircraft specifically tailored for climate-adaptation will likely be required in the 2050 and beyond timeframe to successful adapt to climate changes that might still occur despite ongoing research and development efforts into sustainable aviation by NASA, other governmental research organizations, and Industry. NASA has a long history of studying 'runway independent aircraft' (RIA) – i.e., VTOL (vertical takeoff and landing) and STOL (short takeoff and landing) aircraft of various types. But such studies haven't directly considered the implication of RIA in the context of climate mitigation and climate adaption. Hybrid electric regional CTOL (conventional takeoff and landing) aircraft are currently being studied by NASA ARMD, but only a very small amount of research is being currently studied for hybrid-electric large, regional VTOL and/or STOL aircraft.

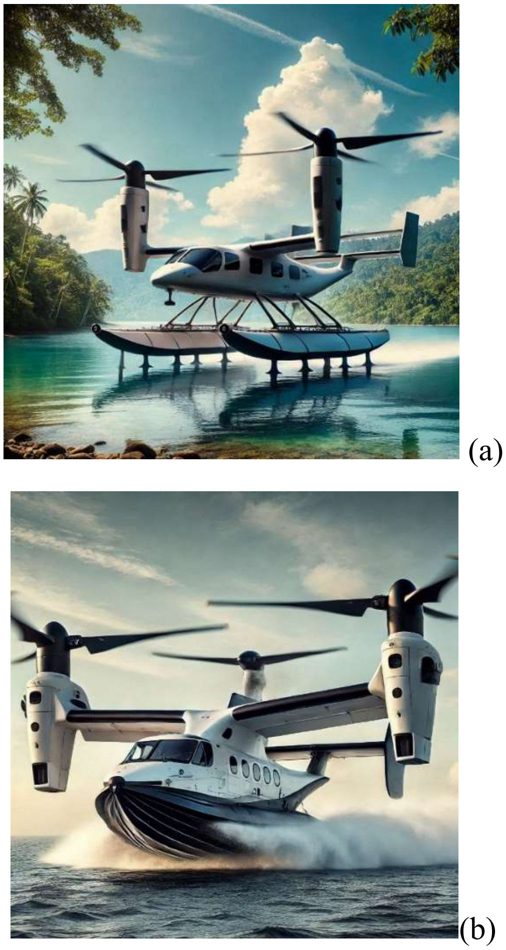


Figure A1. Amphibious runway-independent-aircraft (tiltrotors) conceptual artwork (AI-generated images by Microsoft Copilot): (a) pontoons and (b) seaplane-like hulls

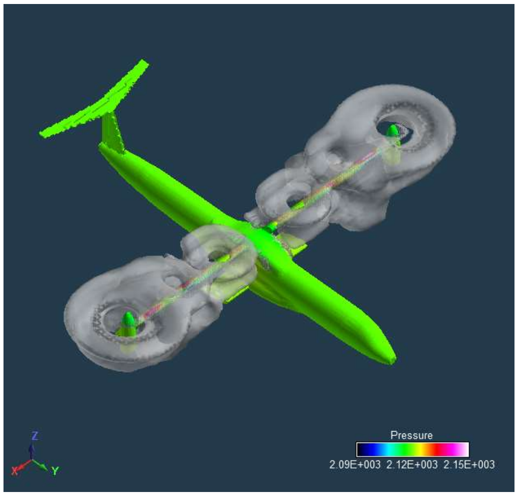
General requirements for an aircraft design element to the CATS project could potentially for an exploratory design study of a V/STOL (vertical and short takeoff and landing) aircraft are outlined below:

1. A required minimum range of 310 miles (500km) on hybrid electric propulsion; a cruise speed of 300knots and 25kft is to be assumed;
2. Aircraft should carry 53 passengers and crew total (assumed per passenger/crew weight of 250lbf);
3. Aircraft should have a minimum of 25% of hover power and 25% of helicopter-mode edgewise forward flight power provided by electrical energy; remaining propulsion energy can be provided by combustion-based energy sources (turboshaft engines); all airplane-mode cruise power can be provided by turboshaft engines; this minimum target might be adjusted through initial studies and discussion;
4. The aircraft should be capable of occasionally landing/taking off vertically, taking off and landing on very short runway lengths (in addition to conventional runways), and taking off and landing occasionally on littoral waterways. From a life cycle mission perspective, an aircraft should have the following attributes: (a) 10% of all life-cycle flights should be vertical takeoff and landing flights that include 2 minute hover, (b) 20% of flights that require short takeoff and landing from very short runway lengths of 500ft, and (c) 50% of flights from large airports with conventional runways of 11kft and (d) 20% of flights requiring amphibious, but otherwise conventional, takeoff and landing for littoral waterways (e.g., Boeing 314 ‘Clipper’ like takeoff and landings).
5. The aircraft should be capable of VTOL, STOL, or CTOL takeoff and landings for high and hot conditions anticipated in the 2050 time frame (5k ISA+30°C, or an increase of 10°C from ‘LCTR2’ design conditions, https://rotorcraft.arc.nasa.gov/Public

ations/files/AHSAcreeFinal_Tiltrotor_1039_12696.pdf); last accessed November 30, 2024.

6. The amphibious takeoff and landings can use lengths on water of 2000ft in sea state of 3 ((1 ft 8 in to 4 ft 1 in), “Slight”) and winds of 30 +/- 15mph;

Some initial mid-fidelity CFD and rotorcraft sizing analysis for the notional vehicle shown in Fig. A2a-c was performed for four different missions phases noted above in requirement #4.



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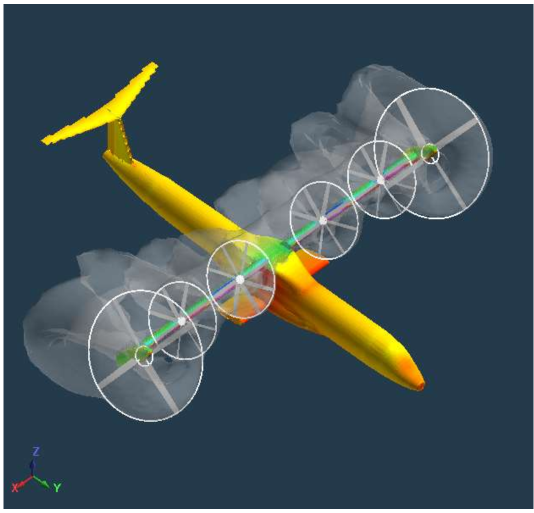

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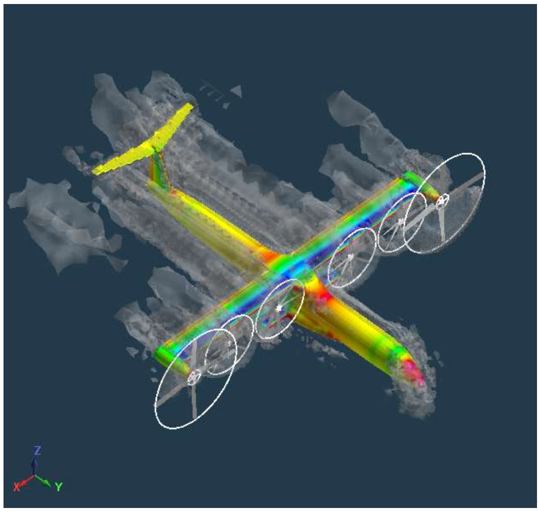

(c)

Figure A2. Amphibious CATS Flyer: (a) VTOL hover, (b) STOL takeoff, and (c) cruise

Table A1 summarizes the results of a simple rotorcraft sizing analysis for the VTOL mission, which is the most challenging mission from a gross weight perspective. This simple rotorcraft sizing analysis was performed using the methodology outlined in Ref. 16. The sizing presented in Table A1 assumes that modular battery packs – and electric motors in parallel in two input combiner gearboxes – and jet-fuel-based turboshaft engines are used for this version of a CATS amphibious flyer. Promising advances in hydrogen-based fuel cells might present an alternate or augmentation to jet-fuel-based turboshaft engines but that will have to be studied more closely in the future.

Table A1. Resulting sizing weight table: VTOL mission profile

Proprotor (larger rotors) Disk Loading	973.2	N/m^2
Propeller (smaller rotors) Disk Loading	1621.9	N/m^2
Proprotor (larger rotors) Radii	4.3	m
Propeller (smaller rotors) Radii	2.3	m
Number of Proprotor Blades	4.0	Nondim.
Number of Propeller Blades	4.0	Nondim.
Proprotor (larger rotors) solidity	0.12	Nondim.
Propeller (smaller rotors) solidity	0.20	Nondim.
Propeller Tip Speeds	238.2	m/s
Nominal (Mean) Airplane-Mode Cruise Wing Loading	4984.6	N/m^2
Wing Span	14.2	m
Number of Electric Motors per Rotor	1.0	Nondim.
Aircraft Total Hover Power	7386.1	kW
Advance Ratio	0.21	Nondim.
Nominal Total Helicopter-Mode Forward Flight Power	5659.9	kW
Ratio of lift carried by the aggregate of tiltwing like propellers to total lift (in hover)	0.5	Nondim.
Vehicle Effective Lift over Drag in Airplane-Mode Cruise	8.0	Nondim.
Nominal (Mean) Airplane-Mode Cruise Power	5059.4	kW
Energy from Battery over Total Mission Energy	0.09	Nondim.
Prescribed Fraction of Power Delivered by Electric Motors in Hover versus Turboshaft Engines	0.25	Nondim.
Prescribed Fraction of Power Delivered by Electric Motors in Helicopter-Mode Forward Flight versus Turboshaft Engines	0.25	Nondim.
Prescribed Fraction of Power Delivered by Electric Motors in Airplane-Mode Cruise versus Turboshaft Engines	0.0	Nondim.
Payload (PAX+Crew)	6022.7	kg
Total Weight of Rotors	1459.7	kg
Fuselage Weight	2665.1	kg
Wing Weight	3472.5	kg
Total Turboshaft Engines and Drive Train Weight	3214.4	kg
Total Fuel Weight	1399.0	kg
Total Battery Weight	2756.0	kg
Total Electric Motor Weight	926.0	kg
Total Fixed Equipment Weight	2279.0	kg
Total TOGW =	21578.9	kg

The third requirement from the above list of mission/design requirements, that only 25% of hover power and 25% of helicopter-mode edgewise forward flight be provided by electrical power, seems to be a rather modest 'sustainable aviation' goal. It is apparent, though, from initial sensitivity study results that increasing these percentages results in substantial weight growth in the vehicle design. This is hardly surprising for rotorcraft. Still, part of the future discussion must be the question of how much growth in vehicle weight is acceptable to meet attendant electric-propulsion goals. This is not just an open issue for rotorcraft but all aircraft that might be designed to meet sustainable aviation goals. The approach of this study is to chip away at the problem, to make slow advancements, to seek to meet modest goals now rather than later.

One way to compensate for the power intensive nature of VTOL is to make the battery packs onboard aircraft modular so that: (a) if battery technology upgrades become available than new, better batteries can be easily swapped out with older batteries, and, most importantly, (b) the aircraft could ideally be reconfigured between VTOL, STOL, and CTOL modes of operation while on the ground, in between flights, in parallel with aircraft refueling with jet-fuel (or hydrogen if fuel-cells are implemented). If the case can be made that such a mode of operation (reconfiguring between flights with modular propulsion elements or batteries) can be performed and is responsive to an economically viable business model and (airport and vertiport) network architecture model than sustainable aviation through (partial) electric propulsion might be viable for rotorcraft.

It is this possibility of using modular batteries that are installed during VTOL, partially installed during STOL, and completely removed for CTOL flights that is considered in Fig. A3. Figure A3 estimates the increased aircraft range as batteries are removed and flight profiles are adjusted for all the major modes of operation suggested in the Fig. A2 amphibious V/STOL (hybrid tiltwing/tiltrotor) aerial vehicle.

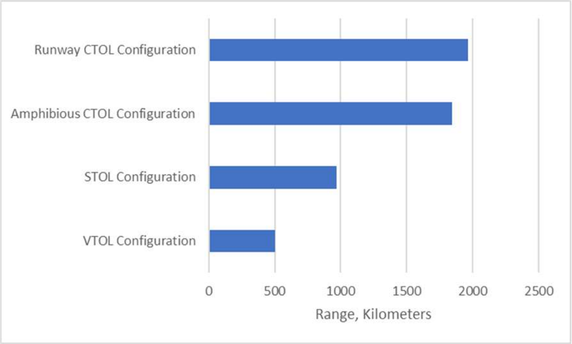

Figure A3. Range for other mission profiles (STOL, CTOL on runway, and CTOL amphibious takeoff) if modular battery packs were removed, if not needed, for a particular flight

Whether climate change impacts will reach to the level that flooding and sea level rise will significantly US airports to the point that artificial islands for airports and the use of amphibious aircraft for commercial travel will be required to adapt is still a question subject to additional research, modeling, and simulation. What does seem more likely, though, is that there are low-lying island nations in the Pacific Ocean – nations which are also highly dependent on tourism – where amphibious commercial transport aircraft might be a well needed lifeline.