Design of a Multi-Tiltrotor Concept Vehicle for Urban Air Mobility

“Version 0” Design

Design Review: Nov 3, 2021

Beau P. Pollard, Jason R. Welstead, and Siena K. S. Whiteside
NASA Langley Research Center

Revolutionary Vertical Lift Technology (RVLT) Project
Advanced Air Vehicle Program, NASA Aeronautics Research Mission Directorate

sacd.larc.nasa.gov/uam

NOTE:

This slide deck presents "Version 0" of the NASA Multi-Tiltrotor UAM Reference Vehicle, in lieu of a formal report. The "Version 0" design was completed Nov 2021; priorities have since shifted so these slides have been made available so as to not further delay publication of the vehicle.

The "Version 0" publication includes:

- Nov 3, 2021 "Version 0" Design slides
- OpenVSP model
- NDARC and AIDEN model

All files are available to download at: sacd.larc.nasa.gov/uam

Outline

1. Background
   - Motivation
   - NASA UAM Reference Vehicles
   - Sizing mission
2. Multi-Tiltrotor Design Process
   - Survey of existing concepts
   - Configuration exploration and downselect
   - Design trades and tuning
3. Results
   - Comparisons with other NASA UAM reference vehicles
4. Summary
5. References

Motivation: Urban Air Mobility[1] (UAM)

Urban Air Mobility[1] (UAM): A safe and efficient air transportation system where everything from small package delivery drones to passenger-carrying air taxis is operating above populated areas.

[1] www.nasa.gov/uam-overview/

Motivation: Urban Air Mobility[1] (UAM)

NASA RVLT[2] Project Technical Challenge: "Tools to Explore the Noise and Performance of Multi-Rotor UAM Vehicles"

GAP

Noise is a likely obstacle to public perception of UAM vehicles. A validated and documented methodology for assessing tradeoffs between noise and efficiency of UAM vehicles does not exist, preventing:

- Assessment of noise impact of UAM vehicles on the community
- Exploration of feasible noise mitigation strategies
- Assessment of vehicle performance requirements imposed by low-noise designs.

OBJECTIVE

Develop, demonstrate, validate, and document a set of conceptual design tools capable of assessing the tradeoffs between UAM vehicle noise and efficiency.

To support this Technical Challenge, a fleet of "UAM reference vehicles"[3] have been designed, at a conceptual level, that are publicly available and intended to be representative of the vehicles that have been proposed for the UAM industry.

[1] www.nasa.gov/uam-overview [2] www.nasa.gov/aeroresearch/programs/aavp/rvlt [3] sacd.larc.nasa.gov/uam

UAM Reference Vehicles[1]

Requirements
- Representative of industry configurations and technologies
- Consistent, known assumptions
- Fully documented & publicly available

Applications
- Common reference models for researchers across UAM community
- Investigate vehicle technologies & identify enabling technologies
- Expose design trades and constraints
- Focus tool development towards needs of UAM
- Simulate vehicle operations (e.g., fleet noise, air traffic integration)
- Aid in industry consensus standards development
- Ride quality simulation

Customers
- NASA, other Government agencies, industry, contractors, academia

Quiet Single Main Rotor Helicopter

Side-by-Side Helicopter

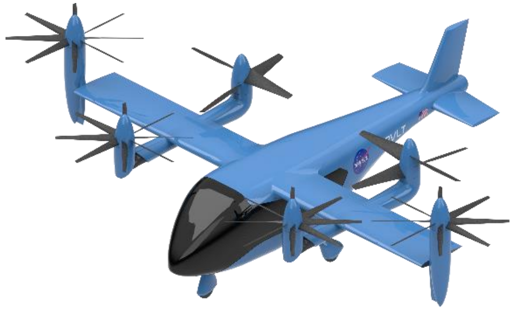
Quadcopter

Lift-plus-Cruise

Tiltrotor

Tiltwing

Tiltduct



Multi-tiltrotor

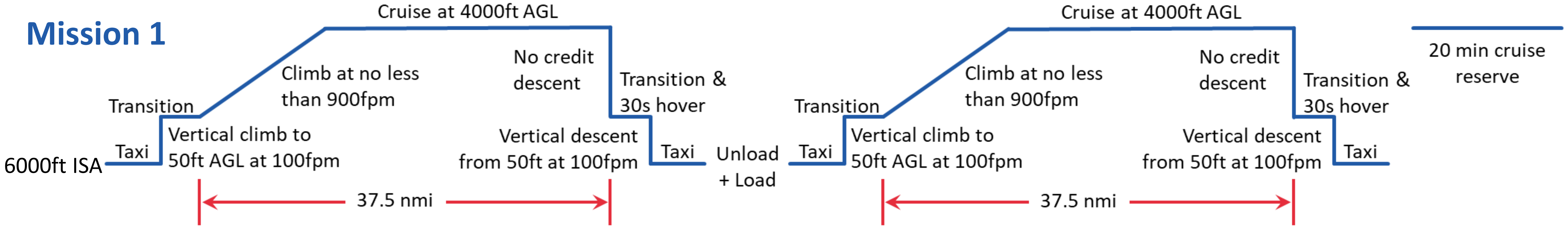
[1] sacd.larc.nasa.gov/uam

Sizing Mission

Mission 1

Most constraining mission from *Patterson et al.*, 2018[1]

- 6 passenger payload (1200 lb)
- 6,000 ft ISA takeoff
- Two 37.5 nautical mile hops into 10 kt headwind
- 20 min cruise reserve at long-range cruise speed



Mission 2

Emergency battery sizing: 2 mins at hover out of ground effect power (30C discharge rate)

Condition 1

Flat-rated MTOW: HOGE at 6000 ft ISA and 100% MRP

Condition 2

Maneuver margin: 500 ft/min cruise climb at 10,000 ft ISA, 100% MRP, DGW.

[1] Patterson, M. D., Antcliff, K. R., and Kohlman, L. W., *A Proposed Approach to Studying Urban Air Mobility Missions Including an Initial Exploration of Mission Requirements*, AHS Forum 74, May 2018.

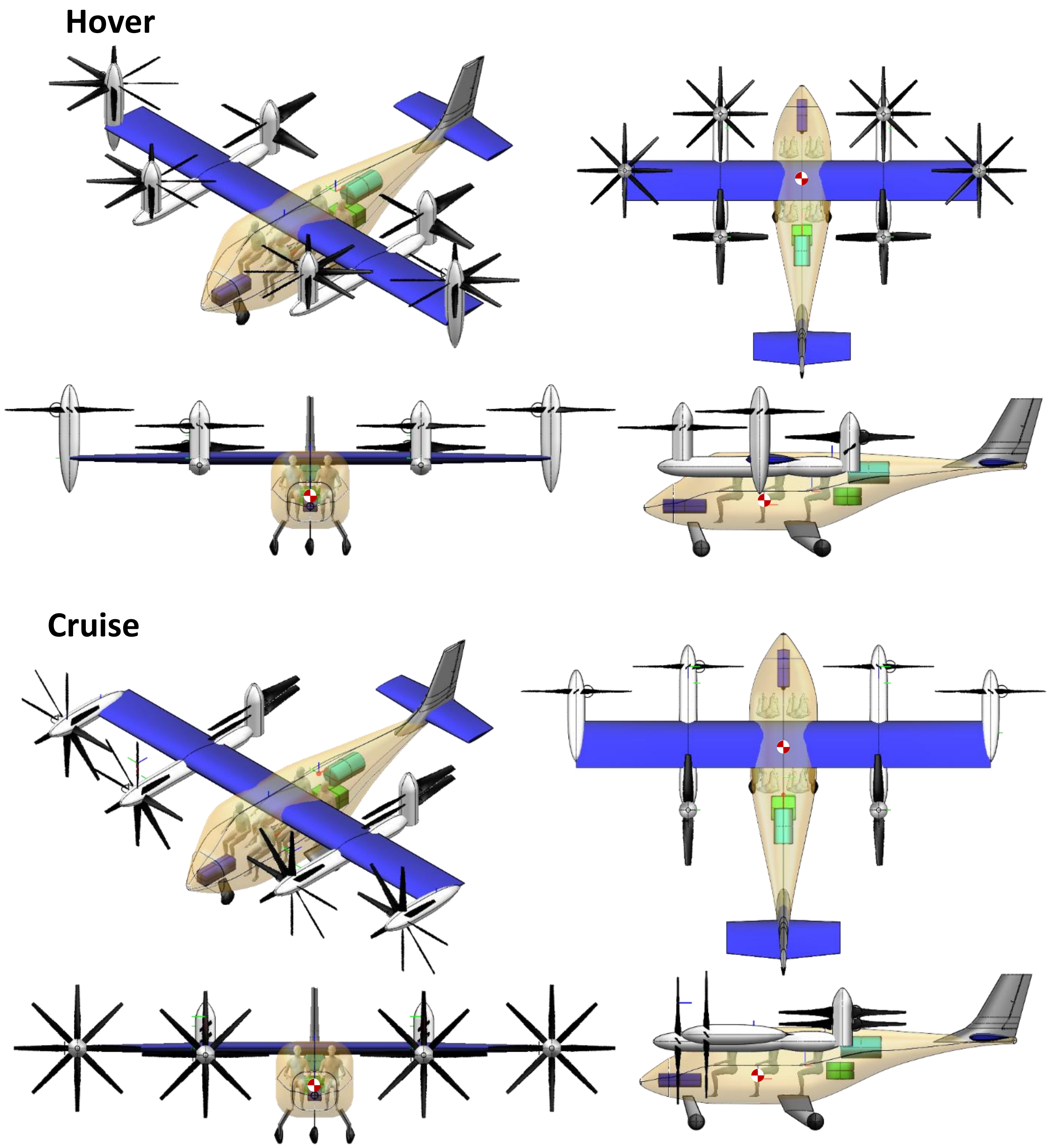
Survey of Industry Tiltrotor Concepts

	Industry Concepts	NASA Multi-Tiltrotor
Maximum Gross Weight (lb)	1,000 – 33,000	~6,000
Number of propulsors	2 – 12	6
Number of passengers	0 – 24	6
Vehicle span (ft)	18 – 50	33
Cruise speed (kt)	60 - 300	150
Range (NM)	35 - 900	75

Tiltrotor concepts:

- XV-15
- V-22
- V-280
- AW 609
- Archer Maker
- Beta Ava XC
- Joby S4
- Overair Butterfly
- Supernal SA-1
- Terrafugia TF-2 Tiltrotor
- Vertical Aerospace VA-X4

Multi-Tiltrotor UAM Reference Vehicle: Key Attributes



- Four eight-bladed tilting proprotors
- Two four-bladed stacked rotors
- Proprotor tip speed $\lesssim$550 ft/s; collective controlled
- Disk loading set to 15 lb/ft^2
- Main wing aspect ratio 8.9
- Wing loading 42.5 lb/ft^2
- Proprotors are laterally separated in cruise to minimize interference
- Proprotors and rotors are laterally and longitudinally separated in hover to minimize interference
- Each tilting proprotor utilizes a two-speed gearbox, and non-tilting rotors have a one-speed gearbox (no cross-shafting)
- Control surfaces: flaperons, flaps, elevator, rudder
- Turboelectric propulsion
- Retractable landing gear

Multi-Tiltrotor UAM Reference Vehicle: Design Process

Survey of 30-40 Past/Current Designs

Initial Sketches & Configuration Exploration

Rapid Sizing Tool modeling of candidate vehicles

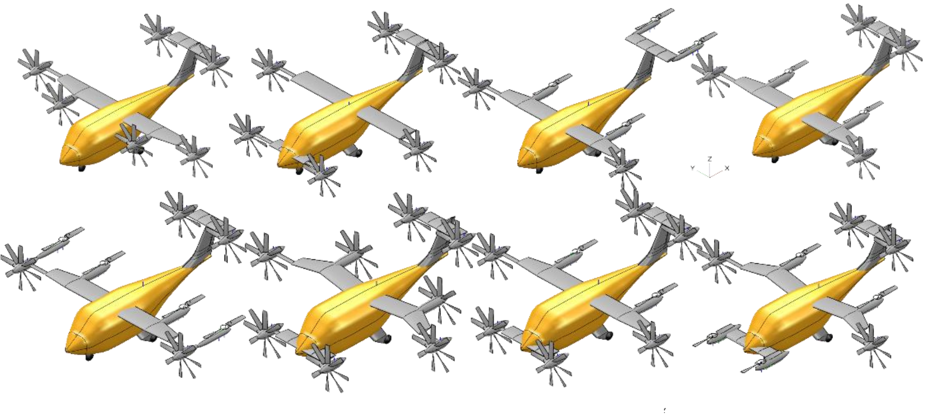
Initial NDARC Modeling

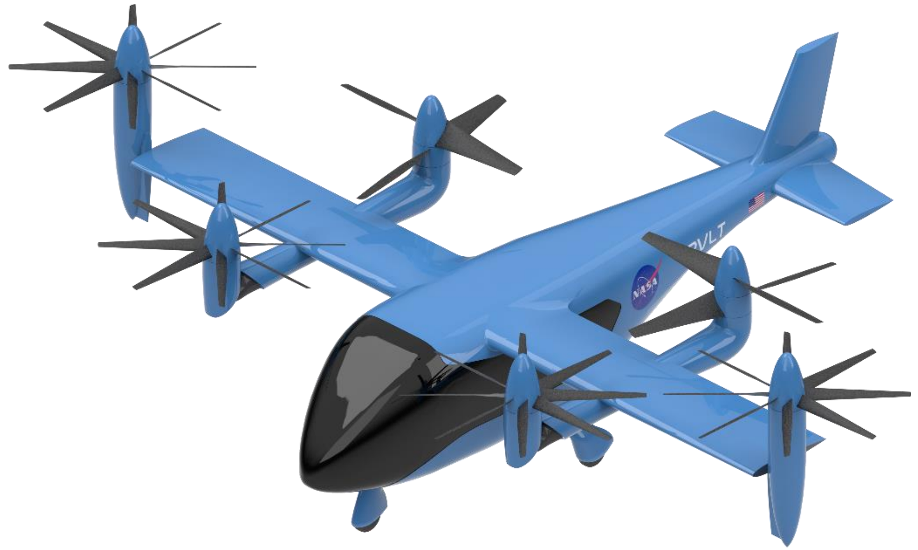
Refinement & Design Trades in NDARC[1]

- Disk Loading
- Performance tuning

Initial Sizing & OML Complete

	Industry Tiltrotor	NASA Multi-tiltrotor
Gross Weight (lb)	1000 - 3000	~6000
No. of Propulsors	2 - 12	6
No. of Passengers	0 - 24	6
Wingspan (ft)	18 - 50	33
Cruise speed (kt)	60 - 300	150
Range (NM)	35 - 900	75

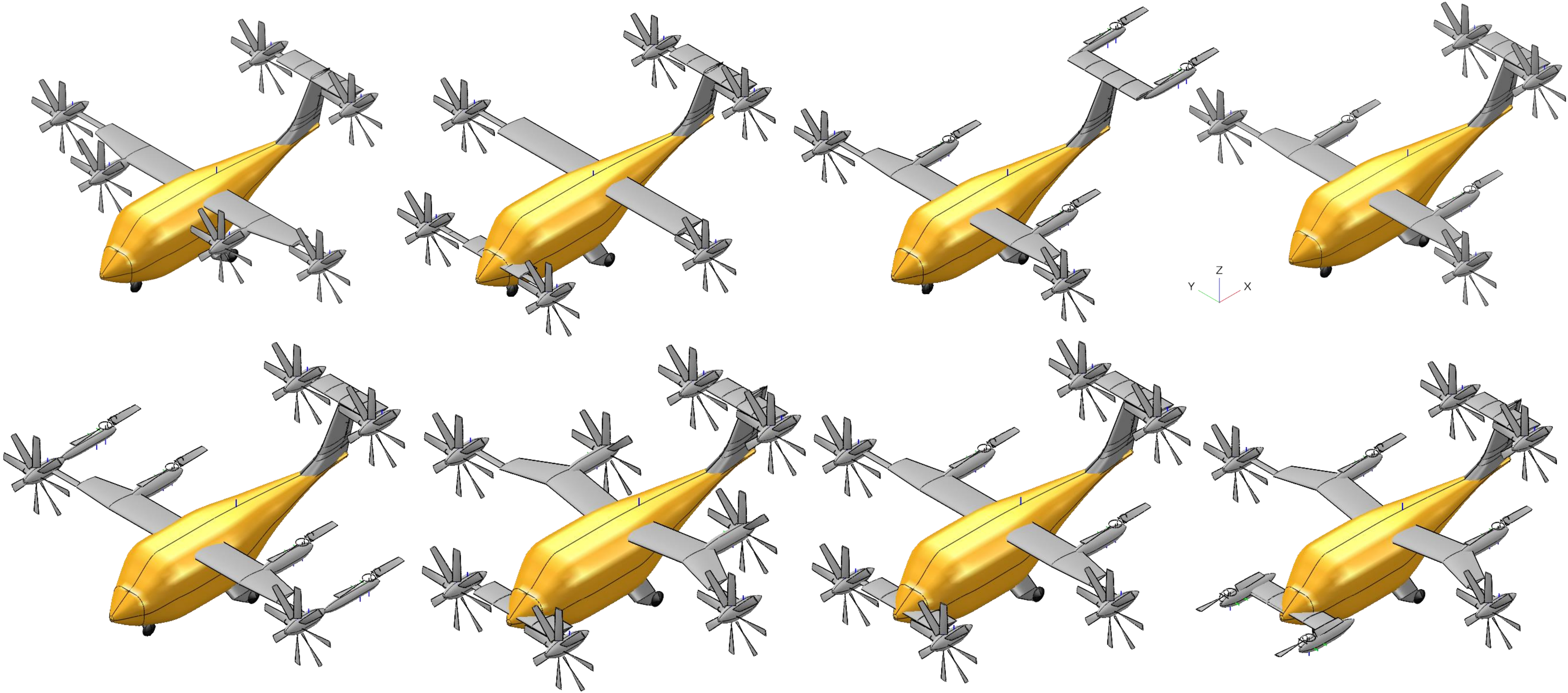




[1] rotorcraft.arc.nasa.gov/ndarc

Configuration Exploration

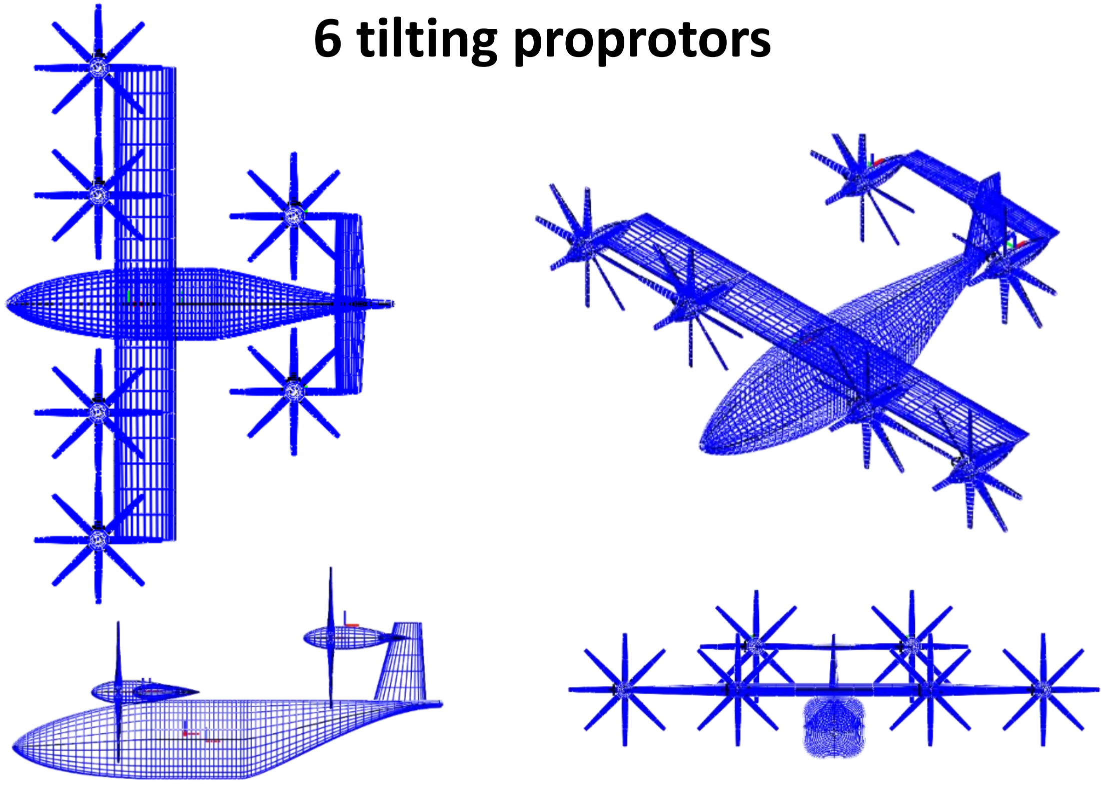
Brainstormed hex (six-rotor) and octo (eight-rotor) configurations; some of the configurations ideated are shown here:



Vehicle configurations were built in OpenVSP: openvsp.org

Hex Configuration Downselect

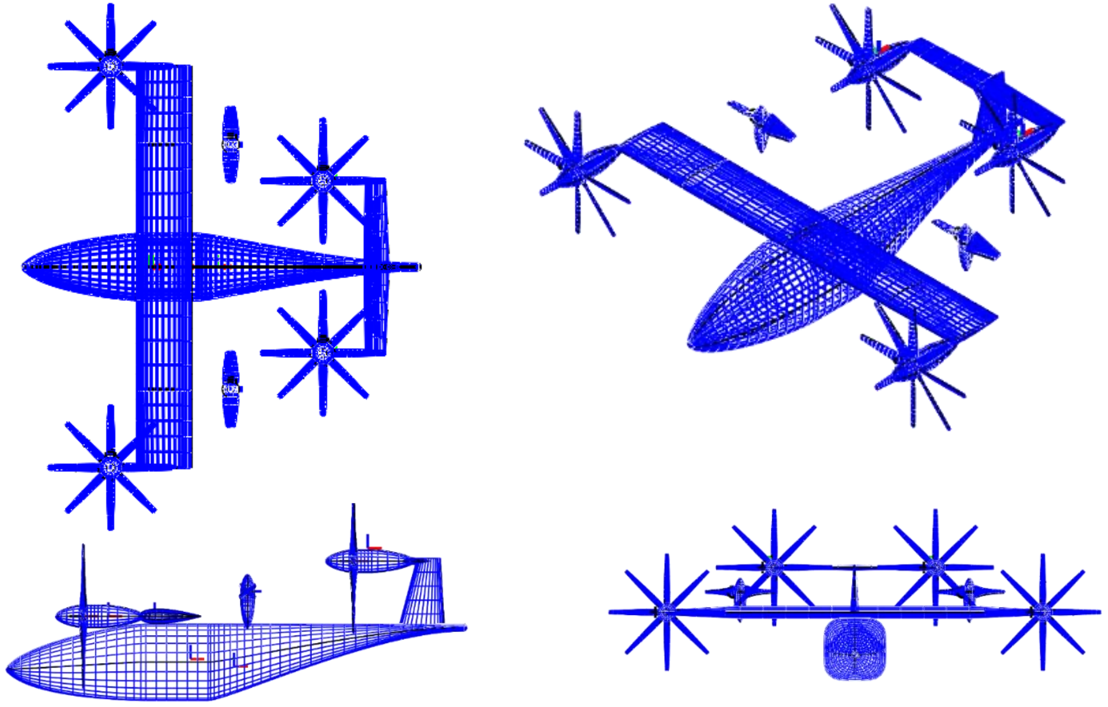
6 tilting proprotors



High-Level Pros:
- All proprotors are identical
- Vertical lift can be longitudinally distributed evenly (hover trim)
- Wingtip prop rotating against wingtip vortex

High-Level Cons:
- Proprotor overlap in cruise

4 tilting proprotors, 2 non-tilting rotors

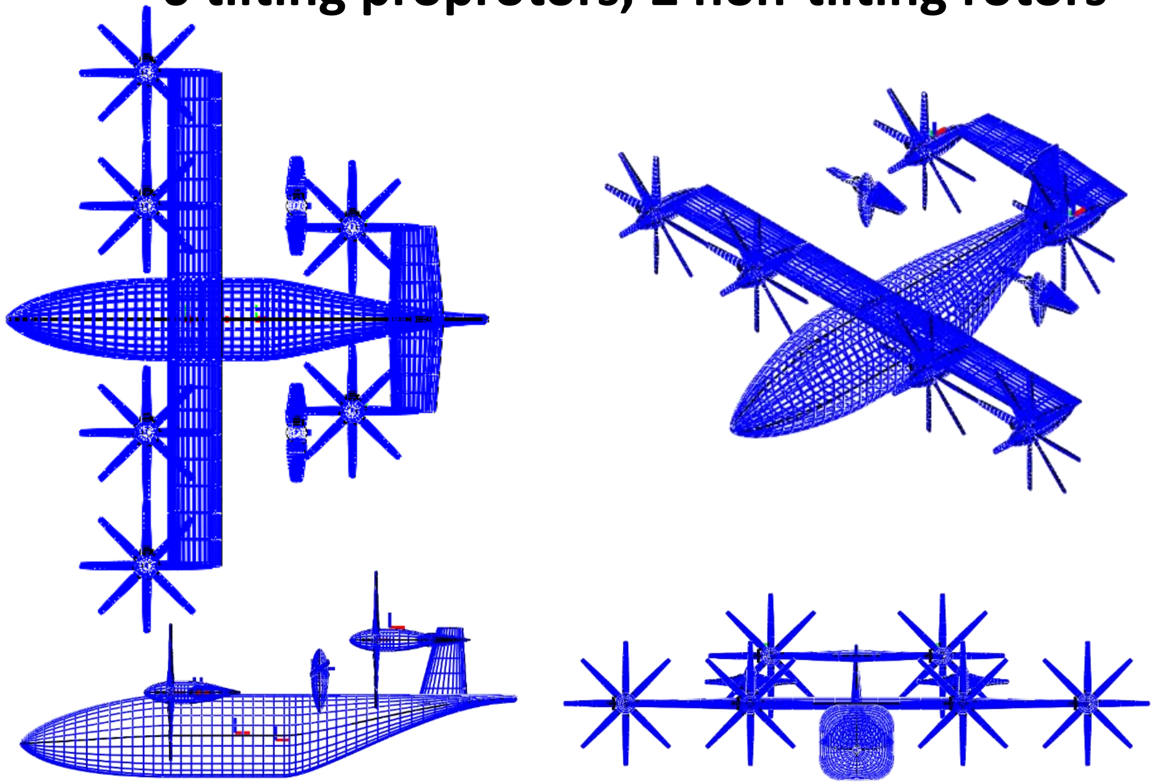


High-Level Pros:
- No proprotor overlap in cruise
- Wingtip prop rotating against wingtip vortex

High-Level Cons:
- Lack of redundancy in hover in tip rotor failure
- Stopped rotor drag reduces cruise efficiency

Octo Configuration Downselect

6 tilting proprotors, 2 non-tilting rotors



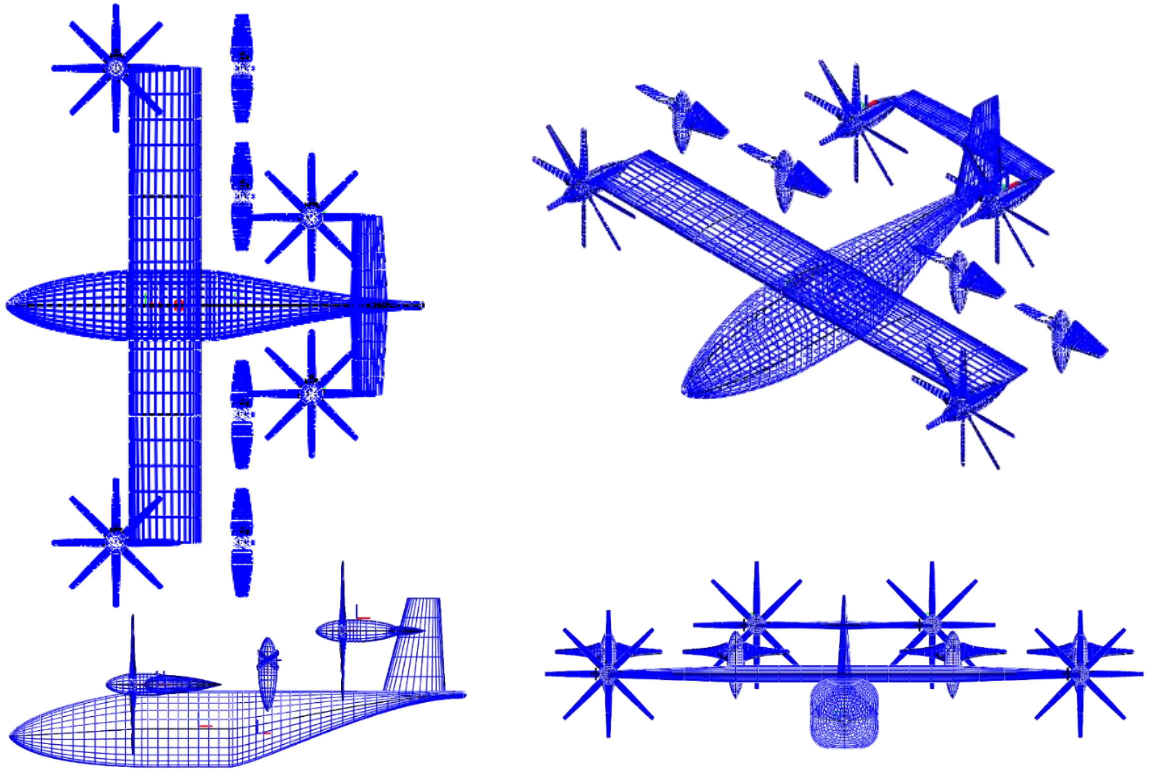
High-Level Pros:

- Vertical lift can be longitudinally distributed evenly (hover trim)
- Wingtip prop rotating against wingtip vortex
- Redundancy

High-Level Cons:

- Inefficient in cruise because of lighter loaded proprotors and drag from stopped rotors

4 tilting proprotors, 4 non-tilting rotors



High-Level Pros:

- Vertical lift can be longitudinally distributed evenly (hover trim)
- Wingtip prop rotating against wingtip vortex
- Redundancy

High-Level Cons:

- Inefficient in cruise because of lighter loaded proprotors and drag from stopped rotors

Configuration Comparison in Rapid Sizing Tool

- Compared the octo and hex configurations using in-house developed Rapid Sizing Tool (RST)
  - RST is a first principles tool utilizing high-level vehicle parameters and momentum theory
  - Utilizes hover and cruise segments to define a mission with user-defined efficiencies to size an electric VTOL vehicle
- Parameters such as figure of merit and lift over drag were set relative to each other
- Parameter sweeps were performed for each configuration using a cell level specific energy of 650 Wh/kg to be consistent with other NASA UAM reference vehicles
- Empty weight fraction was taken from electric Lift-plus-Cruise RVLT reference vehicle[1]
  - Empty weight fraction is also representative of the Archer Maker specifications, which is approximated at 0.61 from publicly available information[2]
- Vehicles were sized in RST using the NASA sizing mission.

	Hex	Octo
Lift over drag (L/D)	12	10
Disk Loading (DL), lb/ft^2	15	15
Figure of Merit (FoM)	0.68	0.7
Proprotor Cruise Efficiency (η_p)	0.8	0.8
Electrical Efficiency (η_e)	0.9	0.9
Induced Power Factor[3]	1.6	1.43
Empty Weight Fraction (EWF)	0.61	0.61

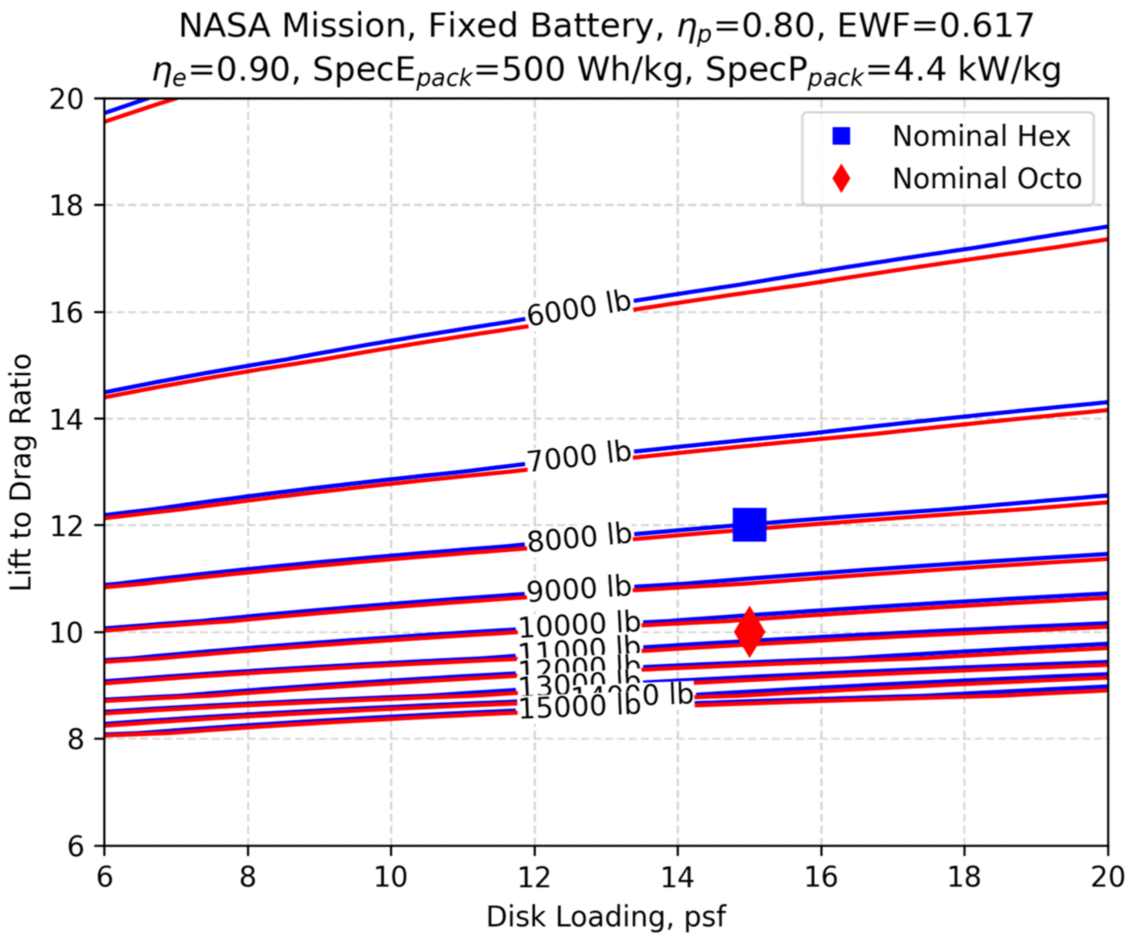
[1] Silva, C., Johnson, W. R., Solis, E., Patterson, M. D., and Antcliff, K. R., "**VTOL Urban Air Mobility Concept Vehicles for Technology Development**," *Aviation Technology, Integration, and Operations Conference*, American Institute of Aeronautics and Astronautics, 2018, ntrs.nasa.gov/citations/20180006683.

[2] Archer Aviation Inc., "**ARCHER**," www.archer.com, accessed 01 Nov 2021.

[3] Induced power factor, $\kappa = P_{induced}/P_{ideal}$

Configuration Comparison in RST

- In RST, the battery specific energy and specific power is either fixed based on a projected technology or optimized for specific power and specific energy
  - ➢ Plot (right) shows a fixed battery specific energy and specific power
- There is not a large difference in the contours between the hex and octo
  - ➢ Battery power is not a constraint in this mission
- Because the contours were relatively similar, we had to make a choice based on the L/D and DL values we thought we could achieve with a specific configuration
- Using 7000 lb as the target maximum Gross Weight, one can see that with a fixed battery we will need a L/D of at least 12, but more likely L/D needs to be approximately 13
- We did not believe that the octo would be able to reach such a high L/D, so eliminated the octo



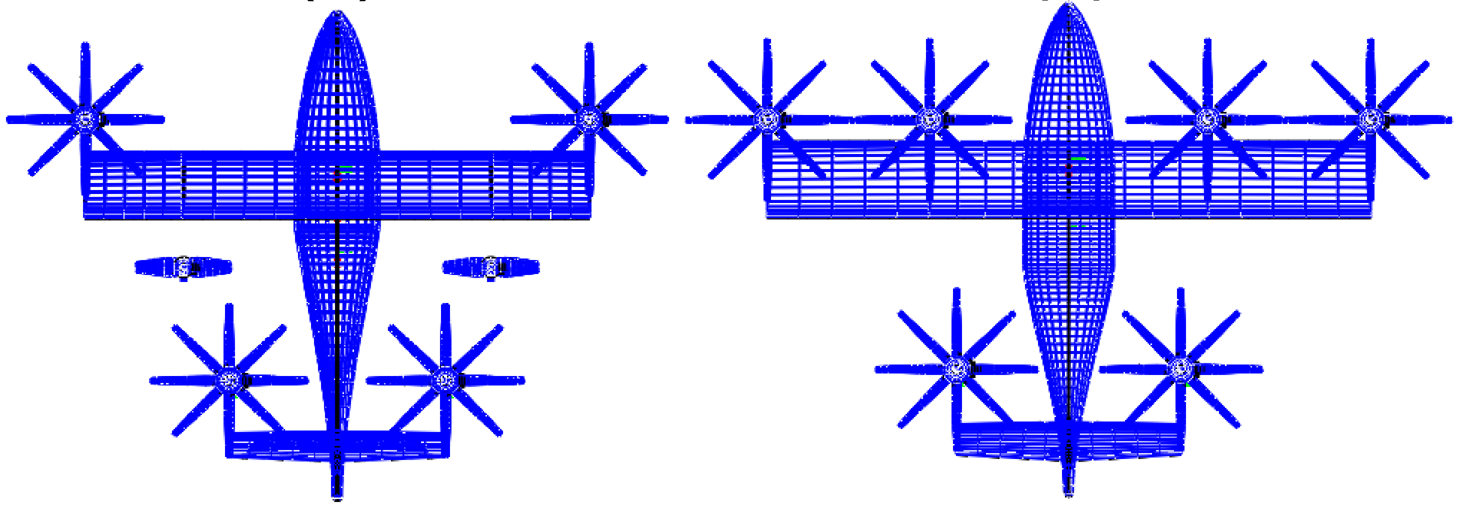
Gross Weight (lb) for variety of lift-to-drag ratios and Disk Loadings (lb/ft^2) using the hex and octo models. Markers show nominal disk loading and lift-to-drag ratios for the two configurations.

Note: SpecE$_{pack}$ and SpecP$_{pack}$ are the battery pack level specific energy and power capabilities, respectively

Choice of Hex Configuration

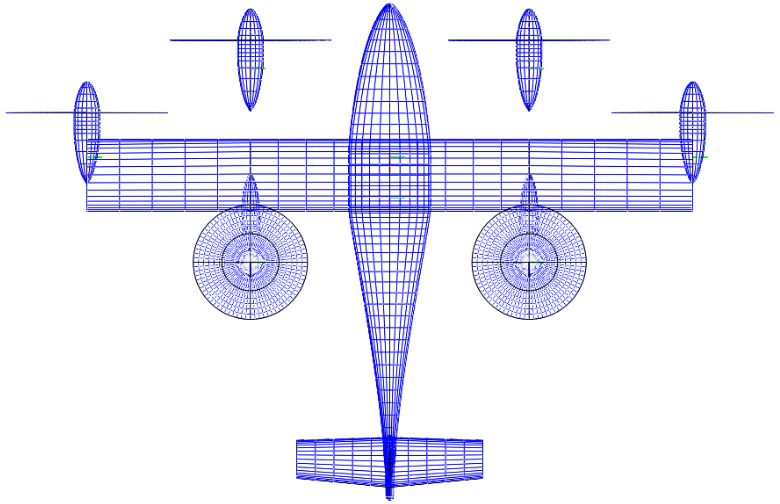
- Two potential hex configurations under consideration (A, B)
- Both configurations had trouble trimming in hover and especially in significant loss of thrust scenarios
- Wanted to provide more longitudinal variation in proprotors about the CG

(A) (B)



- Therefore, mixed components of both configurations to develop new hex configuration (C)

(C)



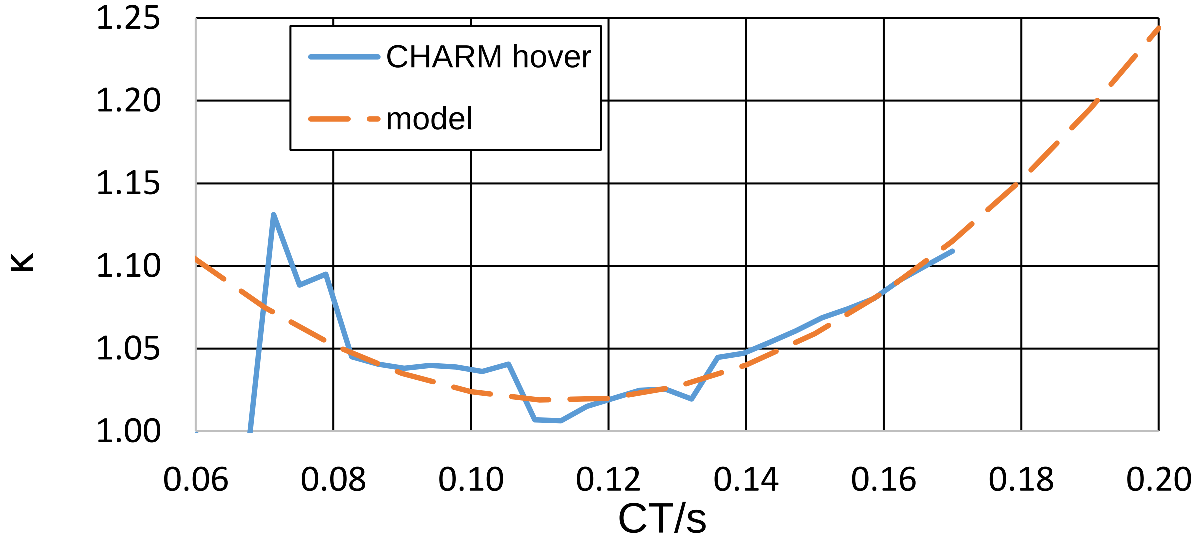
Disk Loading Trade

- Disk loading was varied from 12 to 20 lb/ft^2 in NDARC
- Greater disk loadings led to reduced design gross weights, different from RST
  - Source of RST and NDARC trend discrepancy needs to be explored since matching trends between the two tools have been observed previously
  - Given advanced battery technology assumptions utilized, increased power requirements from high disk loading do not drive the design
- Selected a disk loading of 15 lb/ft^2 because it is a compromise between weight, energy, and cruise speed

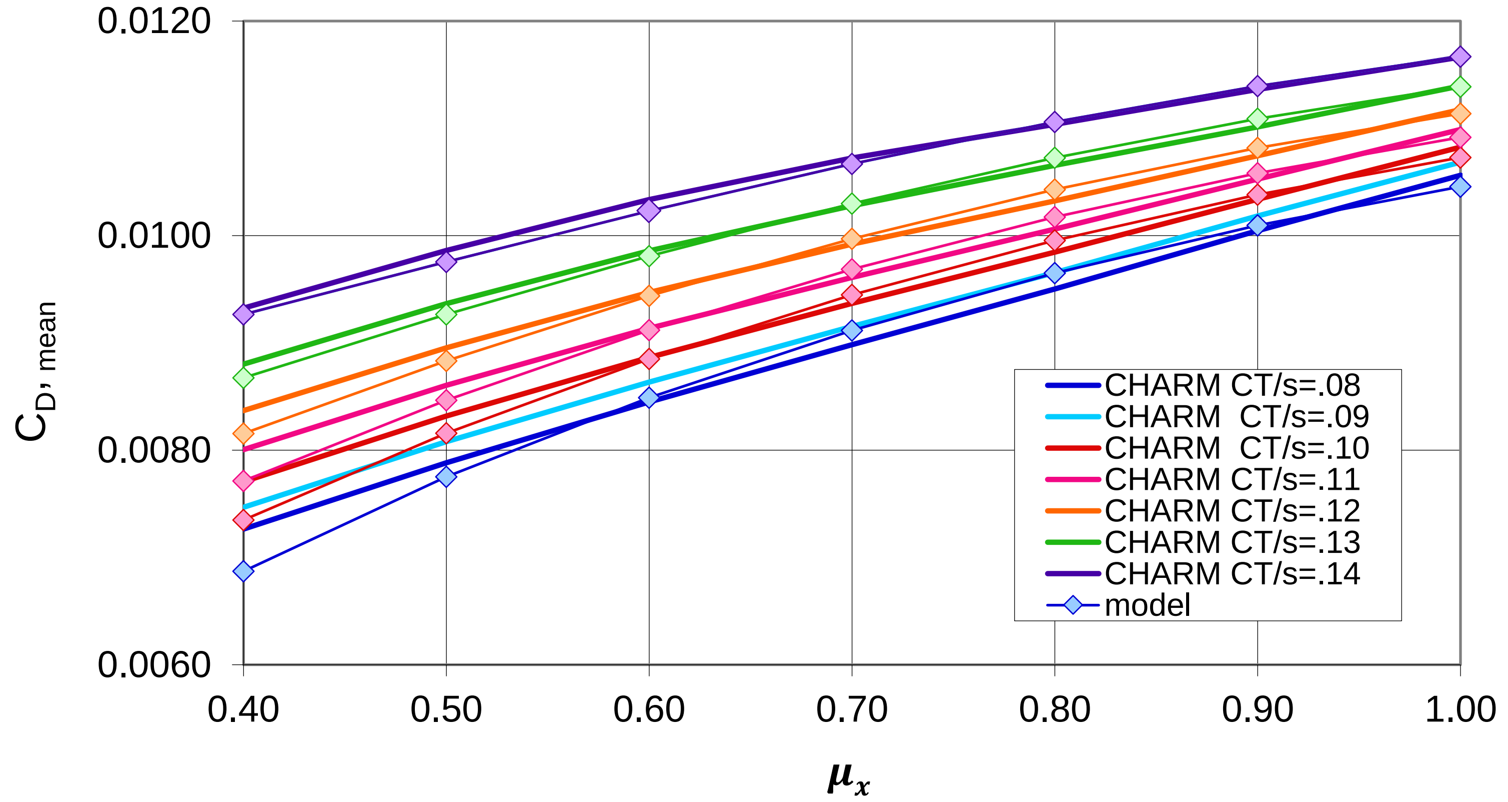
Disk Loading [lb/ft^2]	Design Gross Weight [lb]	Cruise Speed [knots]	Energy Consumed [MJ]
12	6965	150	3164
14	6468	154	3081
15	6355	156	3090
16	6290	159	3117
18	6247	162	3212
20	6275	166	3332

Induced Velocity Tuning

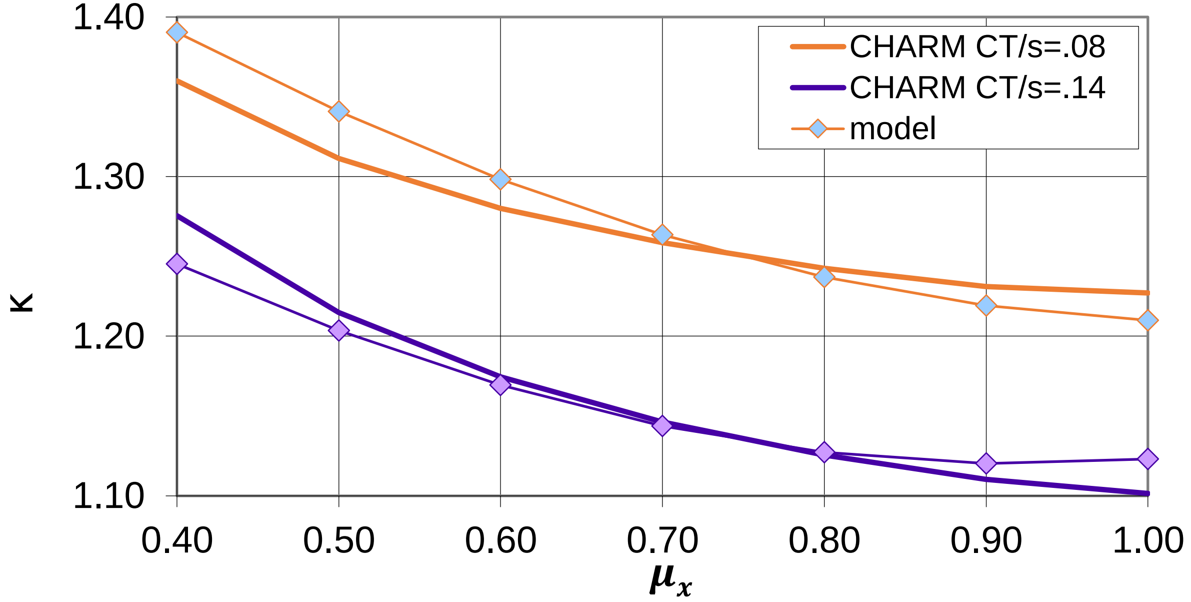
- Used CHARM to tune NDARC's induced power factor, $\kappa = \frac{P_{induced}}{P_{ideal}}$, for hover and cruise flight conditions
- Still needs tuning:
  - Wing Oswald Efficiency
  - Multi-rotor interference



Hover: Induced power factor, κ, versus C_T/σ for CHARM and NDARC models

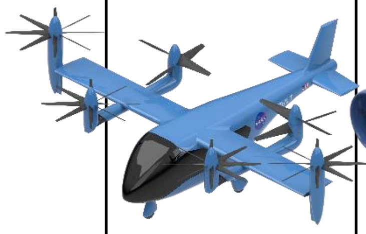
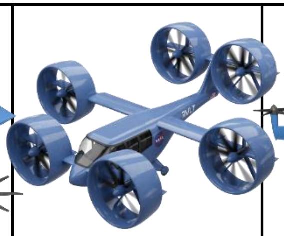


Cruise: Mean drag coefficient versus axial advance ratio, μ_x, for CHARM and NDARC models



Cruise: Induced power factor, κ, versus axial advance ratio, μ_x, for CHARM and NDARC models

Results: Comparison of UAM Reference Vehicles to Date

										
	Multi-tiltrotor *TE*	*Tiltduct* *TE*	Tiltwing *TE*	Lift+Cruise[1] *TE*	Lift+Cruise *E*	Quadrotor *TS*	Quadrotor *E*	Side-by-Side *TS*	Side-by-Side *E*	QSMR[2] *TS*
Max gross weight (lb)	6355	6057	6423	7651	8210	3735	6480	3468	4897	4059
Hover figure of merit	0.71	0.65	0.70	0.63	0.74	0.69	0.70	0.69	0.68	0.74
Block speed (kt)	118.5	115.2	117.3	99.7	91.7	105.0	87.1	97.0	82.6	80.9
L/D_e	9.1	8.0	8.5	7.8	8.5	4.9	5.8	5.9	7.2	5.1
Energy burn (MJ)	3090	2996	3211	3969	1113	2667	1070	2206	686	2868
Wing Area (ft^2)	142	76	126	194	275	N/A	N/A	21	43	N/A

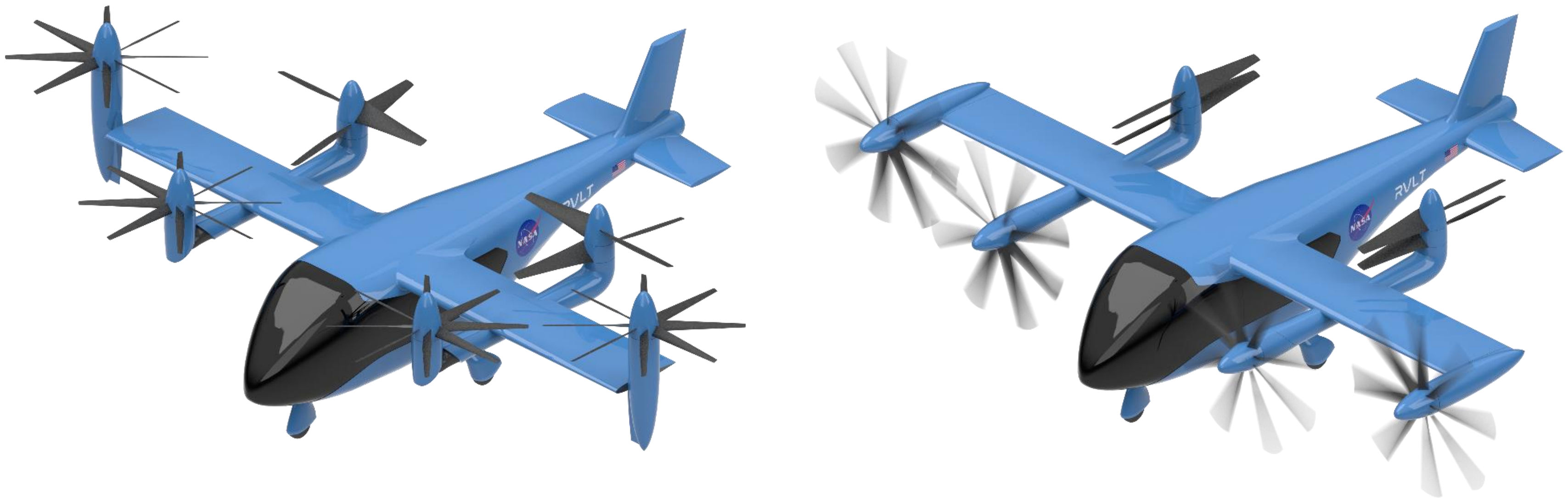
E: Electric
TE: Turboelectric

TS: Turboshaft

[1] Lift+Cruise TE: updated assumptions to maintain consistency with Tiltwing

[2] 450 ft/s tip speed variant

Proposed Future Studies



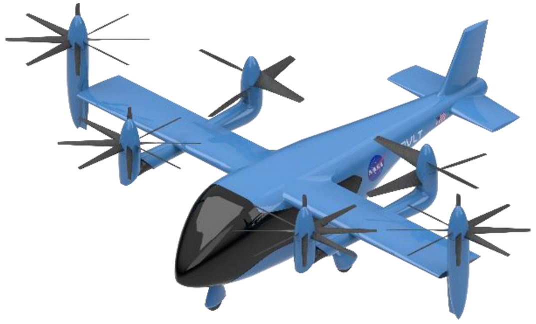
- Design of proprotors and rotors
- Tune NDARC model for proprotor-airframe and proprotor-rotor interactions
- Investigate effect of proprotor and rotor spin directions
- Investigate credible noise reduction technologies
- Improve conceptual design & analytical tools related to this vehicle
- RVLT Validation Test Campaign,[1] FY20-25: UAM-related tests, including proprotor tests

[1] Schaeffler, N. W., "**RVLT Validation Test Plan**," *NASA Acoustic Technical Working Group Meeting*, 08 Oct 2021, ntrs.nasa.gov/citations/20210022605.

Summary

<u>Initial</u> multi-tiltrotor UAM reference vehicle design complete

- “Version 0” multi-tiltrotor added to the NASA UAM reference vehicle fleet
- RST was used to explore broad parameter sweeps; NDARC was used as a basis for sizing the selected vehicle configuration
- Further design work is desired prior to performing trade studies that incorporate this vehicle



Multi-Tiltrotor

Tiltduct

Tiltwing

Quiet Single Main Rotor Helicopter

Side-by-Side

Tiltrotor

Quadcopter

Lift-plus-Cruise

Download
the NASA UAM Reference Vehicles!

Technical reports,
OpenVSP, NDARC, and AIDEN models:

sacd.larc.nasa.gov/uam


NASA
CHASE
Revolutionary Vertical Lift Technologies Project

RVLT UAM Reference Vehicles: Paper References

Johnson, W., Silva, C., and Solis, E., "**Concept Vehicles for VTOL Air Taxi Operations**," *AHS Technical Conference on Aeromechanics Design for Transformative Vertical Flight*, AHS International, 2018, ntrs.nasa.gov/citations/20180003381.

Patterson, M. D., Antcliff, K. R., and Kohlman, L. W., "**A Proposed Approach to Studying Urban Air Mobility Missions Including an Initial Exploration of Mission Requirements**," *AHS International 74th Annual Forum*, AHS International, 2018, ntrs.nasa.gov/citations/20190000991.

Silva, C., Johnson, W. R., Solis, E., Patterson, M. D., and Antcliff, K. R., "**VTOL Urban Air Mobility Concept Vehicles for Technology Development**," *Aviation Technology, Integration, and Operations Conference*, American Institute of Aeronautics and Astronautics, 2018, ntrs.nasa.gov/citations/20180006683.

Kohlman, L. W., and Patterson, M. D., "**System-Level Urban Air Mobility Transportation Modeling and Determination of Energy-Related Constraints**," *Aviation Technology, Integration, and Operations Conference*, American Institute of Aeronautics and Astronautics, 2018, arc.aiaa.org/doi/10.2514/6.2018-3677.

Antcliff, K. R., Whiteside, S. K. S., Kohlman, L. W., and Silva, C., "**Baseline Assumptions and Future Research Areas for Urban Air Mobility Vehicles**" *SciTech Forum and Exhibition,* American Institute of Aeronautics and Astronautics, 2019, ntrs.nasa.gov/citations/20200002445.

Kohlman, L. W., Patterson, M. D., and Raabe, B. E., "**Urban Air Mobility Network and Vehicle Type—Modeling and Assessment**," NASA TM-2019-220072, Moffett Field, CA, 2019, ntrs.nasa.gov/citations/20190001282.

Johnson, W., "**A Quiet Helicopter for Air Taxi Operations**," *VFS Aeromechanics for Advanced Vertical Flight Technical Meeting*, Vertical Flight Society, San Jose, CA, January 21–23, 2020, ntrs.nasa.gov/citations/20200000509.

Whiteside, S. K. S., Pollard, B. P., Antcliff, K. R., Zawodny, N. Z., Fei, X., Silva, C., and Medina, G. L., "**Design of a Tiltwing Concept Vehicle for Urban Air Mobility**," NASA TM-20210017971, Hampton, VA, 2021, ntrs.nasa.gov/citations/20210017971.

Whiteside, S. K. S. and Pollard, B. P., "**Conceptual Design of a Tiltduct Reference Vehicle for Urban Air Mobility**," *VFS Aeromechanics for Advanced Vertical Flight Technical Meeting*, Vertical Flight Society, San Jose, CA, January 25–27, 2022, ntrs.nasa.gov/citations/20210025911.

Radotich, M., "**Conceptual Design of a Tiltrotor Aircraft for Urban Air Mobility**," *VFS Aeromechanics for Advanced Vertical Flight Technical Meeting*, Vertical Flight Society, San Jose, CA, January 25–27, 2022, rotorcraft.arc.nasa.gov/Publications/files/Michael_Radotich_13-Jan-22_03-47-02.pdf.