Updates to NASA Urban Air Mobility Reference Vehicles
Incorporating Recent Technology, Policy, and Economic Developments

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Conceptual Design Tech Lead and Senior Technical Advisor
NASA Revolutionary Vertical Lift Technology Project

VFS Electric VTOL Symposium
Santa Clara, California
6-8 February 2024
We observe very diverse VTOL vehicle solutions

- **Multicopters**
  - Stopping rotor
  - Lift+cruise

- **Tiltrotors and tiltwings**
  - Stop some rotors, tilt some rotors

February 2024
Why we designed the NASA reference vehicles

• Vehicle model inputs and outputs publicly available
  – Discussions can be quantitative
  – Demonstration cases for training
  – Features representative of vehicles
  – Missions and design conditions
  – Margins and reliability requirements

• Focus and guide government research
  – Enable contracted work to be published
  – Assess technology payoff
  – Guide tool development
  – Scope validation tests

• No plan or desire to build the vehicles
  – But these are not cartoons

Count of vehicles in evtol.news listing as of 31 January 2024

February 2024
What is the composition of a reference vehicle model?

- Baseline, excursions, and variants
- Reports
- NDARC design and off-design
- Geometry
- Comprehensive Analysis
- Structures
- Flight Dynamics
What is the composition of a reference vehicle model?

- Baseline, excursions, and variants
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Papers and journal articles

Papers and journal articles

NASA publications

**Concept Vehicles for VTOL Air Taxi Operations**

**Abstract**

Concept vehicles are presented to investigate whether there is an urban air mobility or on-demand mobility application. Considering the design space dimensions of paired passengers and pitch range, aircraft types, and propulsion system, two aircraft are designed: a single-passenger (300 lb payload), Power Range of vehicles with electric propulsion, a new passenger (300 lb payload, 460 lb+ 460 lb of battery), and a larger-scale (700 lb-700 lb of battery) with hybrid propulsion, and a family of vehicles (500 lb-500 lb of battery) designed for a range of missions and work. The research on electric aircraft is focused on aircraft development for emerging aviation markets, particularly VTOL, but not quantum. Research issues are discussed, illustrated by results from the design of the concept vehicles.

**Introduction**

Urban air taxi operations, often known as urban air mobility or on-demand mobility operations, are enabled by vertical takeoff and landing (VTOL) capable, power and energy requirements are explored in this paper. This paper explores the capability of two aircraft to illustrate the trade-offs in design and operation. The primary goal of the present work is to define the characteristics of the concept vehicles that are used to design and validate NASA's research aircraft in support of aircraft development for emerging aviation markets, particularly VTOL, and not quantum.

To meet these objectives, the designs are carried out for enough to identify missing technologies and research requirements.

**Sources:**

- NASA/TP-2021001797

**Design of a Tiltwing Concept Vehicle for Urban Air Mobility**

**Vanna K. S. Wachira, Rose P. Mold, Kevin S. Amrhein, Nicholas T. Zaremski, and Klaudia F. Lomax**

Langley Research Center, Hampton, Virginia

Christopher Silva

Juno Research Center, Adelphi, Maryland

Karen F. Holston

University of Florida, Gainesville, Florida

**Abstract**

The design and development of a tiltrotor concept vehicle is presented. The concept vehicle is designed to operate in an urban environment, with a focus on short takeoff and landing (STOL) performance. The design is evaluated using a set of metrics, including takeoff and landing performance, endurance, and payload capacity. The results indicate that the concept vehicle is capable of meeting the performance goals set for urban air mobility applications.

**Introduction**

The design and development of a tiltrotor concept vehicle for urban air mobility applications is presented. The design and development process is detailed, including the selection of components, system integration, and performance evaluation. The performance metrics for the concept vehicle are presented, including takeoff and landing performance, endurance, and payload capacity. The results indicate that the concept vehicle is capable of meeting the performance goals set for urban air mobility applications.

**Conclusion**

The design and development of a tiltrotor concept vehicle for urban air mobility applications is presented. The results indicate that the concept vehicle is capable of meeting the performance goals set for urban air mobility applications. The design and development process is detailed, including the selection of components, system integration, and performance evaluation. The performance metrics for the concept vehicle are presented, including takeoff and landing performance, endurance, and payload capacity. The results indicate that the concept vehicle is capable of meeting the performance goals set for urban air mobility applications.

**Sources:**

- NASA/TP-2021001797

**June 2021**
What is the composition of a reference vehicle model?

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- Geometry
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NDARC job outputs (text)

Charts of results
What is the composition of a reference vehicle model?

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OpenVSP for initial design

Watertight, smoothed geometry for CFD

Rendered aircraft for communication and engagement
What is the composition of a reference vehicle model?

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- Geometry
- Comprehensive Analysis
- Structures
- Flight Dynamics

Effect captured in NDARC twin rotor interference parameters:

MODEL_twin='side-by-side', Kh_twin=.92,Kf_twin=1.0,

Outboard advancing
Peak L/De ~ 10.5
Peak b/D ~ 0.85-0.9

Outboard retreating
Peak L/De ~ 9.4
What is the composition of a reference vehicle model?

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Tiltwing NASTRAN model

Lift+Cruise cabin crash test article structural components
What is the composition of a reference vehicle model?

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- Comprehensive Analysis
- Structures
- Flight Dynamics
<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Mission Range</th>
<th>Propulsion Type and Topology</th>
<th>Rotor Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadrotor</td>
<td>1, 2, 4, 6</td>
<td>Direct, gear, x-shaft, diesel, battery</td>
<td>Flapping, stiff Nrotor= 4, 6, 8 Rear rotor z/D</td>
</tr>
<tr>
<td>Side-by-side helicopter</td>
<td>6</td>
<td>Turboshaft, parallel hybrid, battery</td>
<td>Rotor y/R Rotation</td>
</tr>
<tr>
<td>Tiltwing</td>
<td>6, 15</td>
<td>Direct, gear, x-shaft Turboshaft, turboelectric, battery</td>
<td>Collective+trim, monocyclic</td>
</tr>
</tbody>
</table>

Reference vehicles for UAM: baselines & some trades we have performed

**“Air taxi”**

**“UAM”**

Johnson, “Concept Vehicles for VTOL Air Taxi Operations,” January 2018
- Vehicle type
- Mission range
- Propulsion type and topology
- Rotor control

February 2024

Green = Initial exploratory baseline (2018 AHS SF)
Blue = 6 pax baseline (2018 AVIATION, 2020 VFS SF, 2020 AVIATION)
### Reference vehicles for UAM: baselines & some trades we have performed

<table>
<thead>
<tr>
<th></th>
<th>Quadrotor</th>
<th>Side-by-side helicopter</th>
<th>Tiltwing</th>
<th>Lift+cruise compound</th>
<th>Quiet single main rotor helicopter</th>
<th>Tiltduct</th>
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</thead>
<tbody>
<tr>
<td><strong>“Air taxi”</strong></td>
<td><img src="image1" alt="Quadrotor" /></td>
<td><img src="image2" alt="Side-by-side helicopter" /></td>
<td><img src="image3" alt="Tiltwing" /></td>
<td><img src="image4" alt="Lift+cruise compound" /></td>
<td><img src="image5" alt="Quiet single main rotor helicopter" /></td>
<td><img src="image6" alt="Tiltduct" /></td>
</tr>
<tr>
<td><strong>“UAM”</strong></td>
<td><img src="image1" alt="Quadrotor" /></td>
<td><img src="image2" alt="Side-by-side helicopter" /></td>
<td><img src="image3" alt="Tiltwing" /></td>
<td><img src="image4" alt="Lift+cruise compound" /></td>
<td><img src="image5" alt="Quiet single main rotor helicopter" /></td>
<td><img src="image6" alt="Tiltduct" /></td>
</tr>
<tr>
<td><strong>Occupants</strong></td>
<td>1, 2, 4, 6</td>
<td>6</td>
<td>6, 15</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td><strong>Rotors</strong></td>
<td>RPM, collective Flapping, stiff Nrotor= 4, 6, 8 Rear rotor z/D</td>
<td>Rotor y/R Rotation</td>
<td>Collective+trim, monocyclic, coll+tiltrotor DEP</td>
<td>RPM, collective Rotor z/D</td>
<td>NOTAR</td>
<td>Collective with TBD duct trades</td>
</tr>
<tr>
<td><strong>Propulsion</strong></td>
<td>Direct, gear, xshaft Turboshaft, diesel, battery</td>
<td>Turboshaft, parallel hybrid, battery</td>
<td>Direct, gear, xshaft Turboshaft, turboelectric, battery</td>
<td>Turboelectric, battery</td>
<td>Turboshaft, battery</td>
<td>Turboelectric, battery</td>
</tr>
<tr>
<td><strong>Noise tech</strong></td>
<td>Tip speed, tip shape, rear rotor z/D</td>
<td>Tip speed, tip shape, rotor y/R, rotation, IBC</td>
<td>Tip speed, rotor z/D, pitch trim</td>
<td>NOTAR Droop Sweep IBC HHC</td>
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<tr>
<td><strong>February 2024</strong></td>
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</tr>
</tbody>
</table>

**Green** = Initial exploratory baseline (2018 AHS SF)  
**Blue** = 6 pax baseline (2018 AVIATION, 2020 VFS SF, 2020 AVIATION)
What have people been (publicly) doing with the models?

- Electric propulsion
- Flight dynamics, handling/ride qualities
- Structures
- Crashworthiness
- Noise
- CFD+CSD
- Wind tunnel
- NASA

281 papers using the NASA UAM reference vehicles as of 1 January 2024

- Boeing
- CDI
- US Industry
- NASA UAM reference vehicles

- US Army
- CDI+MIT+FAA

- Academia
- NDSU
- UCSD+SDSU+UCD+BYU+
- Aurora+M4
- Georgia Tech

- US Government

- US Industry
Tip speed: Quadrotor most (noise) improvement in approach

<table>
<thead>
<tr>
<th>Tip speed (ft/s)</th>
<th>∆ Takeoff (EPNdB)</th>
<th>∆ Flyover (EPNdB)</th>
<th>∆ Approach (EPNdB)</th>
<th>∆ Empty Wt (%)</th>
<th>∆ Block time (%)</th>
<th>∆ Flyaway (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>375</td>
<td>-3.9</td>
<td>0.2</td>
<td>-7.0</td>
<td>9%</td>
<td>18%</td>
<td>14%</td>
</tr>
<tr>
<td>400</td>
<td>-3.2</td>
<td>-2.0</td>
<td>-7.1</td>
<td>14%</td>
<td>10%</td>
<td>25%</td>
</tr>
<tr>
<td>450</td>
<td>-1.3</td>
<td>-0.9</td>
<td>-3.7</td>
<td>5%</td>
<td>7%</td>
<td>10%</td>
</tr>
<tr>
<td>500</td>
<td>-0.5</td>
<td>0.2</td>
<td>-2.4</td>
<td>1%</td>
<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td>550</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>600</td>
<td>0.3</td>
<td>0.9</td>
<td>3.0</td>
<td>-3%</td>
<td>-2%</td>
<td>-3%</td>
</tr>
<tr>
<td>650</td>
<td>0.9</td>
<td>1.6</td>
<td>5.7</td>
<td>-7%</td>
<td>-3%</td>
<td>-6%</td>
</tr>
<tr>
<td>700</td>
<td>2.1</td>
<td>2.5</td>
<td>8.1</td>
<td>-9%</td>
<td>-1%</td>
<td>-9%</td>
</tr>
</tbody>
</table>

Baseline
Loose-coupled CFD: Can we minimize bad interactions? (Ventura Diaz)

Performance trends similar to comprehensive analysis. Magnitudes vary.
More detailed look into rotor-rotor interactions (Ventura Diaz)

- Wakes impact downstream rotors
- Mid-fidelity tools predict the cost / benefit
- High-fidelity to confirm effects (or not!)

Comprehensive Analysis
1 pax

CFD+CA
6 pax

February 2024
If you can predict productive interference, might as well measure it

Side-by-Side Test Rig for rotor performance in Army 7x10

February 2024
VMS testing and handling qualities analysis

- RPM sluggish and sloppy if motors not capable of at least 2x the torque required for steady operation
  - Pilots really dislike sluggish RPM
  - Passengers dislike sloppy RPM
  - Motor sizing needs to be updated
- Small rotors for reasonable RPM control
  - This is one argument for Distributed Electric Propulsion (DEP)
  - Somewhere around 5 ft radius probably the cutoff, but not sure yet
Fantastic news! We get to do more engineering!

Some of it did not: roof did not keep the high-mass items out of the passenger volume.

Some of it matched our models: sub floor, seats.
The UAM landscape was a bit different in early 2018
Some major policy developments in Europe and USA

**EASA Special Condition for VTOL (SC-VTOL-01, October 2018)**
- Allowing operation into and at low altitudes above European urban areas
- No single point of failure in rotating parts
- 10^-9 catastrophic failures per flight hour over populated areas

**EASA Means of Compliance published (May 2020; MOC-4 SC-VTOL, December 2023)**

**Proposed Special Condition: Electric/Hybrid Propulsion System (SC-E-19, January 2020)**

**FAR Part 23 vs Part 21.17(b) powered lift (May 2022)**
- May be similar to tiltrotor requirements
- 2-control trainer aircraft
(Just a few of the many) New companies and changed vehicles

- Boeing-Wisk partnership
- Volocopter VoloCity
- Moog buys SureFly
- Archer unveils midnight
- Wisk unveils Generation 6
- Joby acquires Uber Elevate
- Joby production prototype
- Boeing buys Aurora
- OverAir unveils Butterfly concept
- Vertical unveils VX-4 concept
- Beta developing CTOL CX300
Crashes in full-scale flight test

Aurora PAV

Joby S4

Vertical VX4

2018 2019 2020 2021 2022 2023 2024
Incremental updates and additions to NASA UAM Reference Vehicles
Updated NASA UAM Reference vehicles

Rotors
- 1+1
- 2
- 4
- 8 + 1

Tilting
- Yes
- Yes
- Yes
- Yes

RPM?
- Variant: 8
- Variant: 8

Stopping?
- Yes: 8
- Yes: 8

February 2024
Updated NASA UAM Reference vehicles

Rotors
- 1+1
- 2
- 4
- 8 + 1

Tilting
- Yes
- Yes
- Yes
- Yes

RPM?
- Variant
- Yes: 8
- Yes: 8

Stopping?
- Yes: 2
- Yes: 2
- Yes: 8
Updated NASA UAM Reference vehicles

- **Rotors**: 1+1
- **Tilting**: Yes
- **RPM?**: Yes: 8
- **Stopping?**: Yes: 8

February 2024
Updated NASA UAM Reference vehicles

- **Rotors**
  - 1+1
  - 2
  - 4
  - 8 + 1

- **Tilting**
  - Yes
  - Yes
  - Yes
  - Yes

- **RPM?**
  - Yes: 8
  - Yes: 8
  - Yes: 4
  - Yes

- **Stopping?**
  - Yes: 8
  - Yes: 8
  - Yes: 2

- **February 2024**
Updated NASA UAM Reference vehicles

Rotors
1+1
2
4
8 + 1

Tilting
Yes
Yes
Yes
Yes

RPM?
Yes
Yes
Yes
Yes

Stopping?
Yes
Yes
Yes
Yes

February 2024
Part 36H Certification Approach Noise Prediction

![Graph showing noise prediction against maximum takeoff weight](image)

- **Noise** (EPNdB) vs. **Maximum Takeoff Weight (kg)**
- **Approach Stage**
  - Stage 2
  - Stage 3

February 2024
When will updated UAM Reference Vehicle models be available?

<table>
<thead>
<tr>
<th>Year</th>
<th>Jan-Mar</th>
<th>Apr-Jun</th>
<th>Jul-Sep</th>
<th>Oct-Dec</th>
<th>Jan-Mar</th>
<th>Apr-Jun</th>
<th>Jul-Sep</th>
<th>Oct-Dec</th>
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<tbody>
<tr>
<td>2024</td>
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<tr>
<td>TBD Future</td>
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</tbody>
</table>

February 2024
How can you get the models?

- **NDARC website – NDARC Users**
  - [https://rotorcraft.arc.nasa.gov/ndarc/](https://rotorcraft.arc.nasa.gov/ndarc/)
  - Request NDARC: [https://software.nasa.gov/software/ARC-16265-1](https://software.nasa.gov/software/ARC-16265-1)

- **Langley Research Center - Systems Analysis and Concepts Directorate- Aeronautics Systems Analysis Branch (LaRC SACD ASAB) – Publicly available**
  - [https://sacd.larc.nasa.gov/uam.refs/](https://sacd.larc.nasa.gov/uam.refs/)

- **NASA Technical Reports Server – Publicly available (reports only)**
  - [https://ntrs.nasa.gov](https://ntrs.nasa.gov)