Simulating Air Taxi Safety: NASA's Quadcopter in Ground Effect

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Towards Urban Air Mobility

- Urban Air Mobility (UAM) is envisioned to be a safe and efficient air transportation system, where everything from small package delivery drones to passenger-carrying air taxis will operate in urban areas

NASA is contributing to this revolution in aeronautics

NASA's RVLT UAM Concept Vehicles

Side-by-Side
(Intermeshing Rotors) [1]

Tilt-Wing
(Airplane mode for efficient cruise flight, helicopter mode for VTOL) [4]

Quadcopter
(Vertically-Separated Rotors) [2]

Quiet Single-Main Rotor (QSMR)
(NOTAR, specifically designed for quiet operations) [3]

- *Reference vehicles contain relevant UAM features and technologies*
- *6 pax VTOL; 2 x 37.5 mile mission with 10 kt headwind; 20 min cruise reserve*

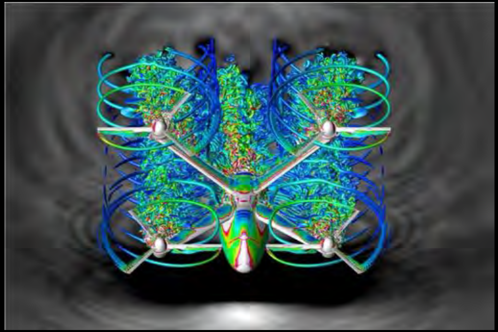
Lift+Cruise
(Hybrid-Mounted Rotors)

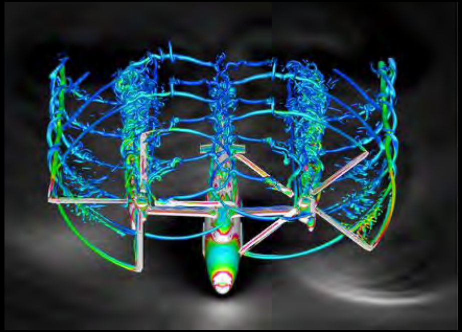
[1] Ventura Diaz, P., Johnson, W., Ahmad, J., and Yoon, S., "The Side-by-side Urban Air Taxi Concept," AIAA Paper 2019–2828, June 2019.
[2] Ventura Diaz, P., and Yoon, S., "High-Fidelity Simulations of a Quadrotor Vehicle for Urban Air Mobility," AIAA Paper 2022–0152, January 2022.
[3] Ventura Diaz, P., Garcia, D., and Yoon, S., "Computational Analysis of a Quiet Single-Main Rotor Helicopter for Air Taxi Operations", VFS Forum May 2022.
[4] Garcia, D., Ventura Diaz, P., and Yoon, S., "High-Fidelity Simulations of a Tiltwing Vehicle for Urban Air Mobility", AIAA Paper 2023-2282, January 2023.

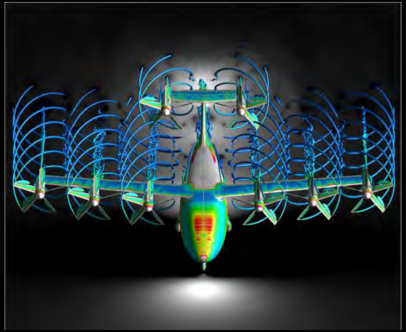
Motivation

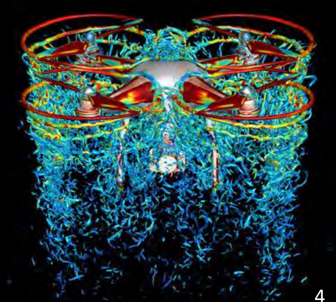
- Current design tools for UAM vehicles use empirical models that are based on historical data that is biased toward traditional Vertical Take-Off and Landing (VTOL) vehicle configurations.
- This can result in inadequate models since most UAM vehicles have very non-traditional VTOL configurations.

Use high-fidelity CFD and overset structured grids to accurately model the moving rotors, solve the flow and calculate aerodynamic performance, for UAM concept vehicles.









NASA's supercomputers: Pleiades, Electra and Aitken

- Located within NASA Advanced Supercomputing (NAS) facility at NASA Ames Research Center.
- CFD is key to be able to visualize and understand the complex flows. It helps us design the future flying vehicles.

Pleiades

Electra

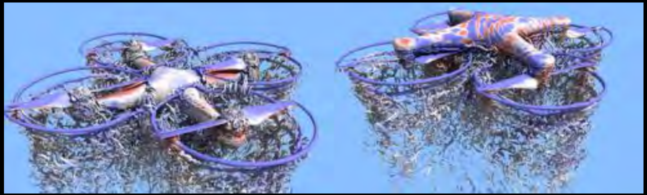
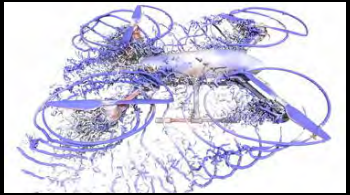
Aitken

NUMERICAL APPROACH

High-Fidelity CFD

OVERFLOW is a high-order accurate Navier-Stokes solver

- Solves the unsteady Reynolds-averaged Navier-Stokes (RANS) equations
- Structured overset grids
- 5th order accurate central differences with scalar dissipation for convective terms
- 2nd order accurate dual time-stepping
- Hybrid RANS/LES turbulence models
  - Spalart-Allmaras one equation turbulence model
  - DDES length scale
  - $y^+ \leq 1$

T. H. Pulliam, "High Order Accurate Finite-Dierence Methods: as seen in OVERFLOW", AIAA Paper 2011-3851

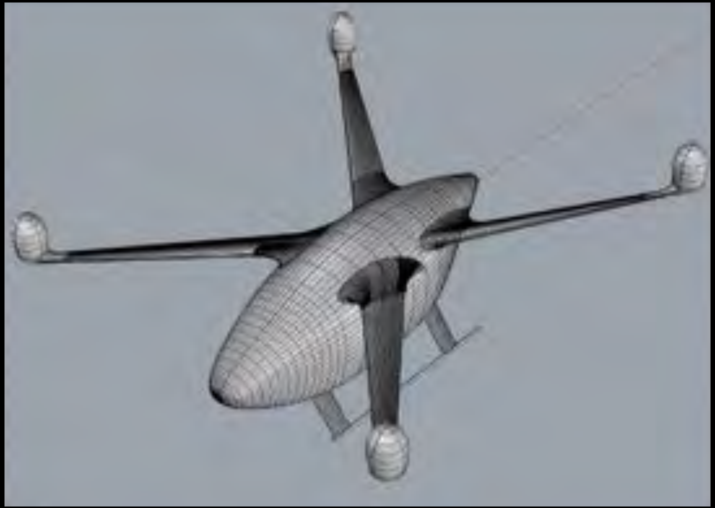
Overset Grid Generation

Chimera Grid Tools (CGT)

CGT is NASA's overset grid generation software

Four main steps in overset grid generation:

- **Geometry processing**: Geometry obtained from CAD or 3D scan techniques



CAD for NASA's quadrotor

W. Chan, R. Gomez, S. Rogers, and P. Buning, "Best Practices in Overset Grid Generation", AIAA Paper 2002-3191

Overset Grid Generation

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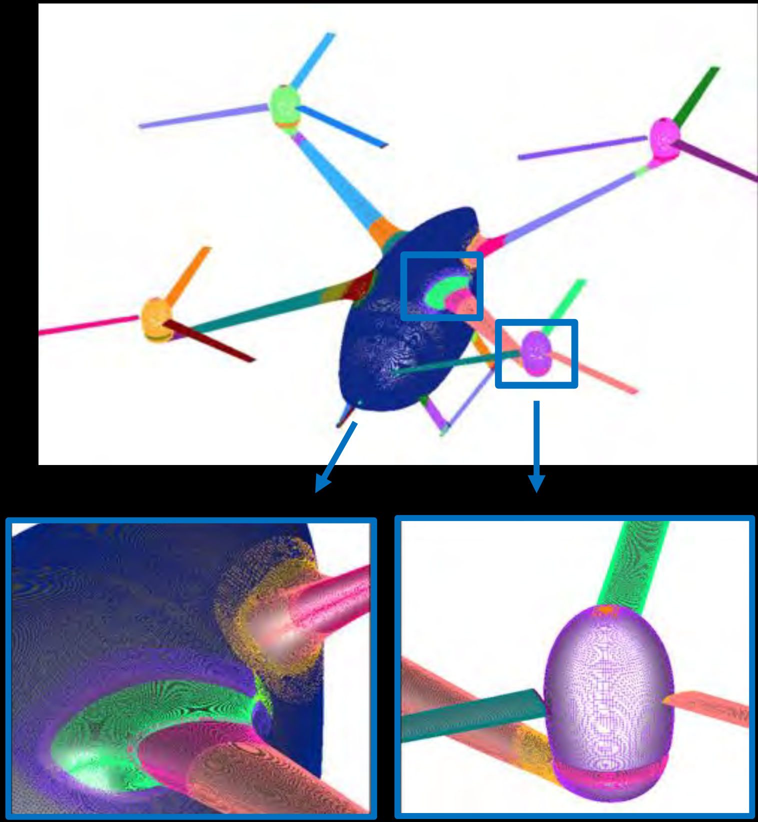
- **Geometry processing**: Geometry obtained from CAD or 3D scan techniques
- **Surface Grid Generation**: feature based domain decomposition, grid point distribution, mesh fill

Complete vehicle surface grids



W. Chan, R. Gomez, S. Rogers, and P. Buning, "Best Practices in Overset Grid Generation", AIAA Paper 2002-3191

Overset Grid Generation

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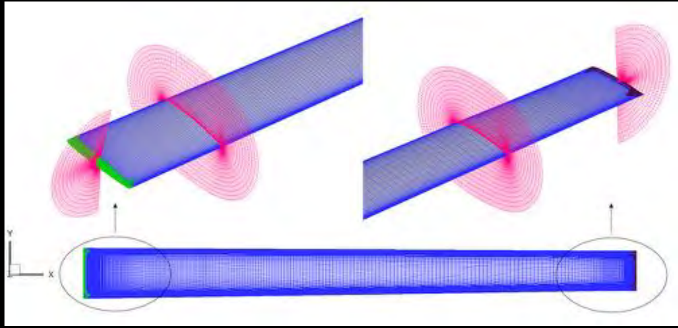
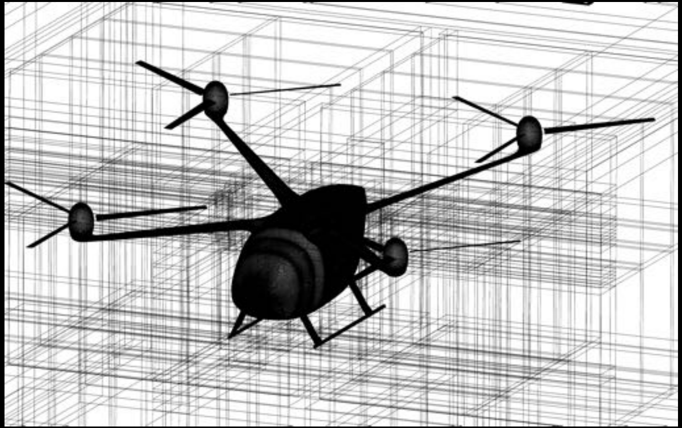
Four main steps in overset grid generation:

- **Geometry processing**: Geometry obtained from CAD or 3D scan techniques
- **Surface Grid Generation**: feature based domain decomposition, grid point distribution, mesh fill
- **Volume Grid Generation**:
  - Hyperbolic Near-Body (NB)
  - Cartesian Off-Body (OB)





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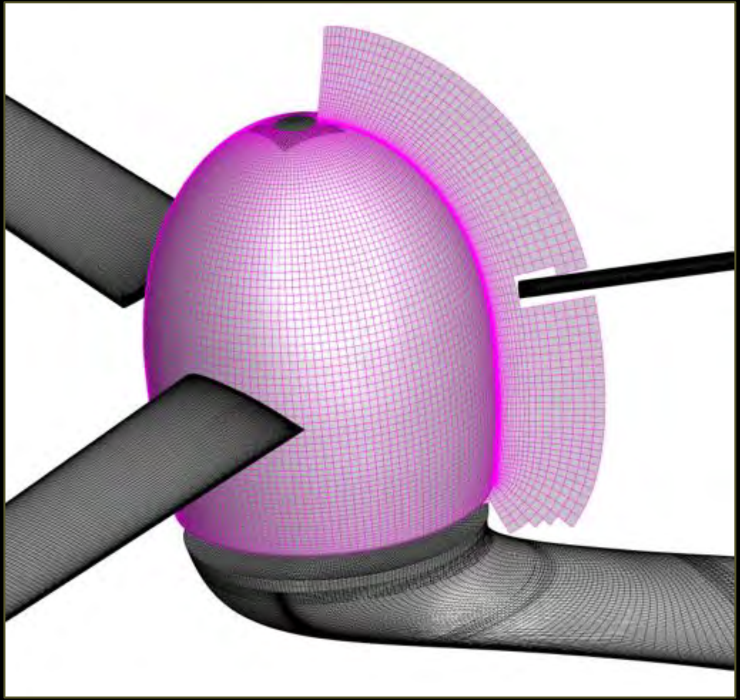
  - Cartesian Off-Body (OB)
- **Domain Connectivity**: grid points blanking, donor stencil search



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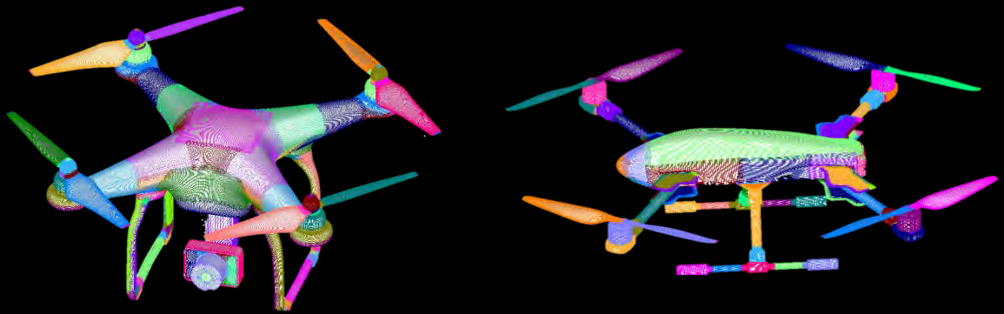
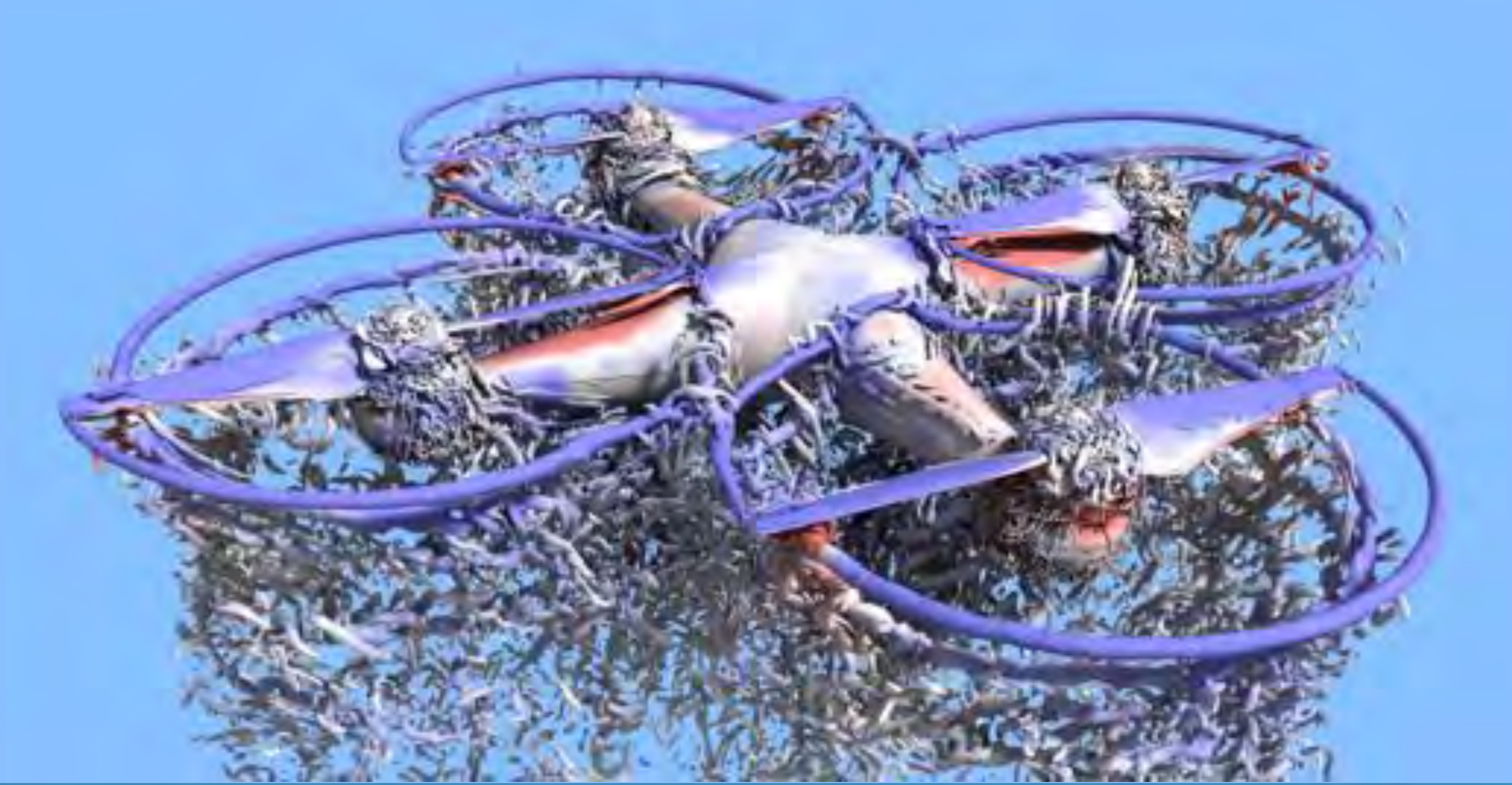
RESULTS



RPM control

UNMANNED VEHICLES

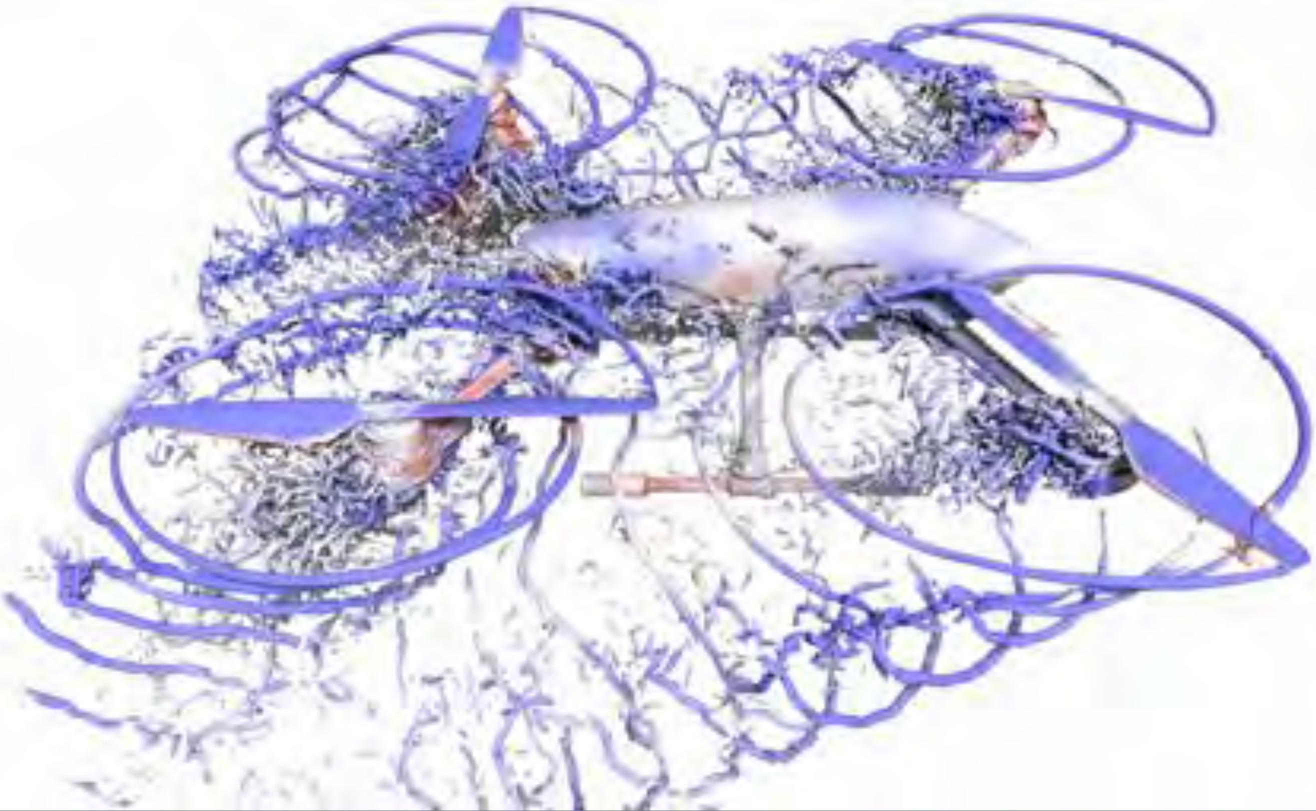
DJI Phantom 3 Quadcopter – Standard Configuration (Overmounted Rotors)



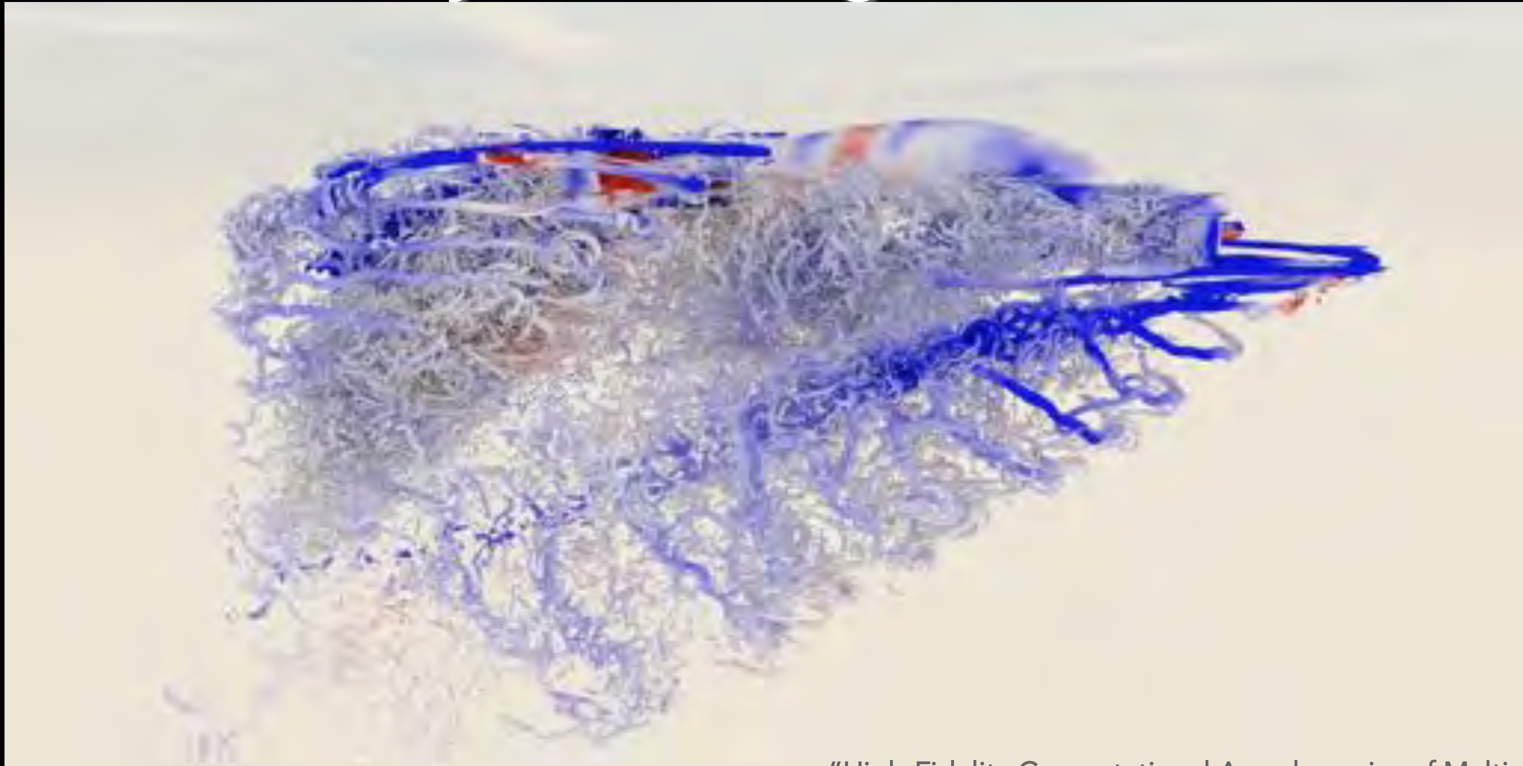
DJI Phantom 3 Quadcopter – Undermounted Rotors

DJI Phantom 3 Octocopter – Coaxial Counter-Rotating Rotors

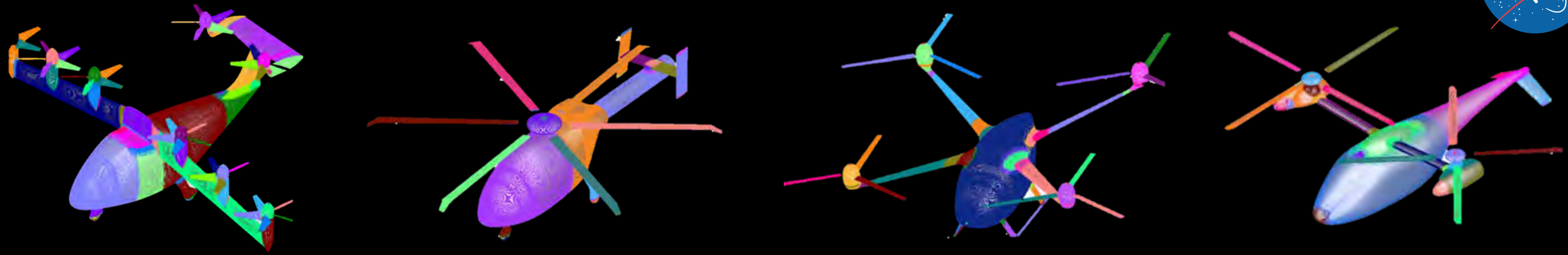
SUI Endurance Quadcopter – Standard Configuration



SUI Endurance Quadcopter – Hybrid Configuration



"High-Fidelity Computational Aerodynamics of Multi-Rotor Unmanned Aerial Vehicles",
P. Ventura Diaz and S. Yoon, AIAA Paper 2018-1266



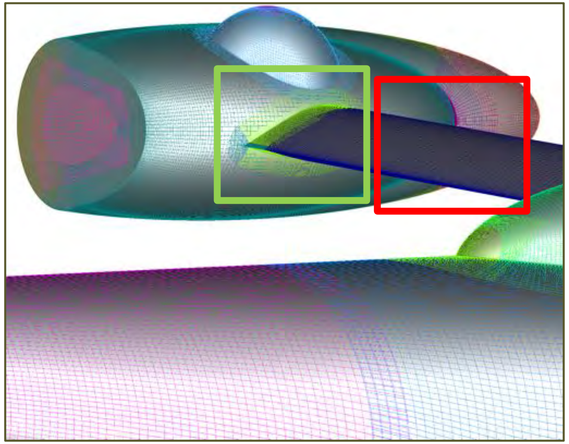
Collective control

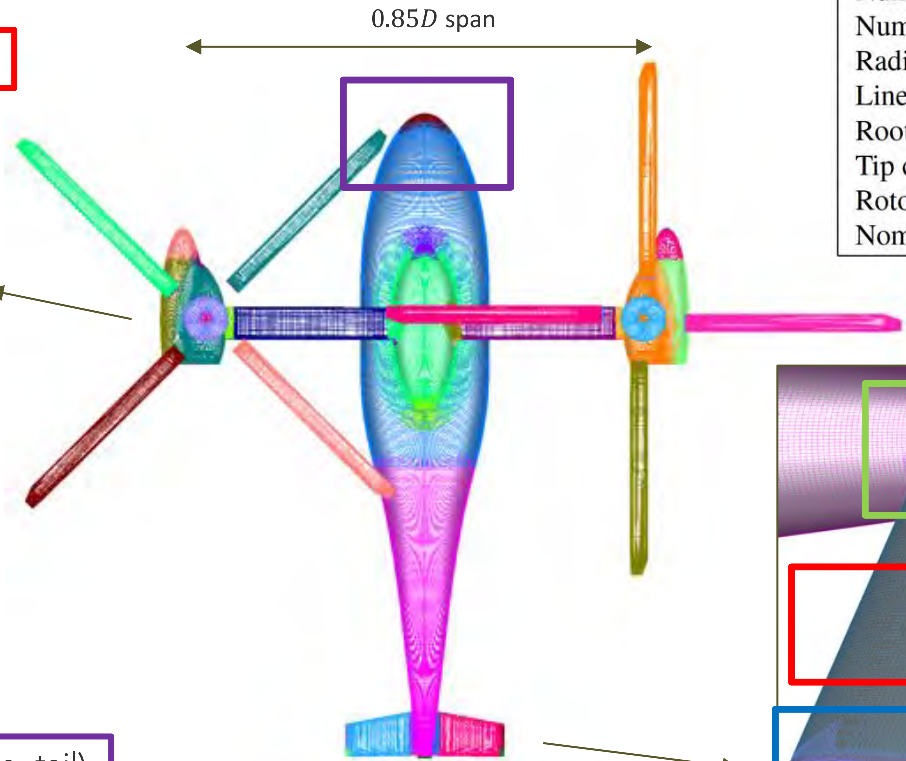
AIR TAXIS

Side-by-side
Quadcopter
QSMR
Tiltwing

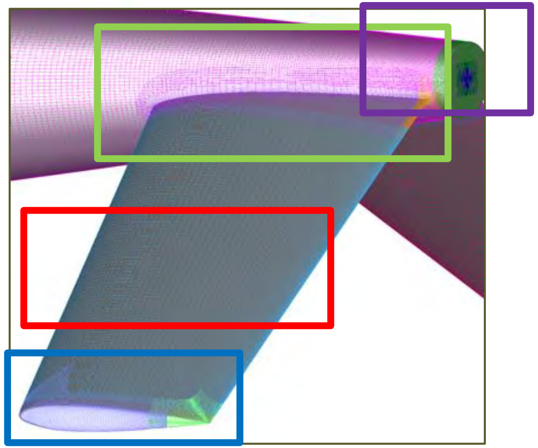
Side-by-side air taxi

O-grids for blades, wing-struts, V-tail





Number of rotors	2
Number of blades/rotor	4
Radius, R	3.203 m
Linear twist	-16 deg
Root chord, c_{root}	0.217 m
Tip chord, c_{tip}	0.130 m
Rotor solidity, σ	0.0832
Nominal tip speed, V_{tip}	167.6 m/s

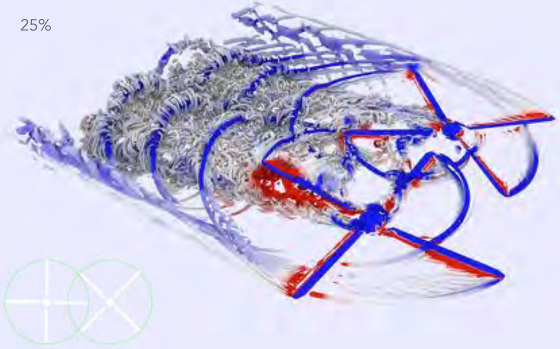


Cap grids for blade tip/root, v-tail

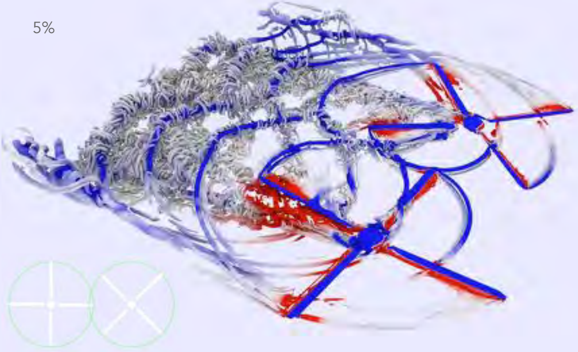
Collar grids for junctions

Axis cap grids for singular points (nose, tail)

25%



5%



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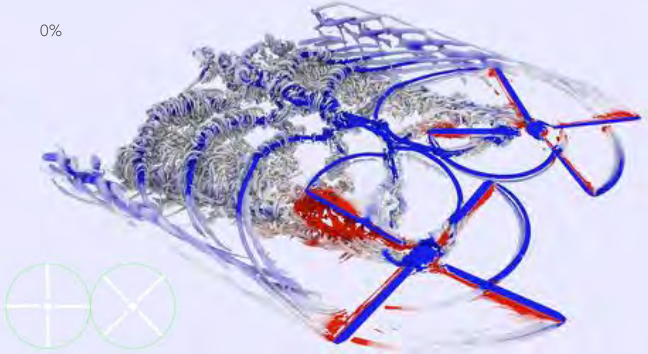
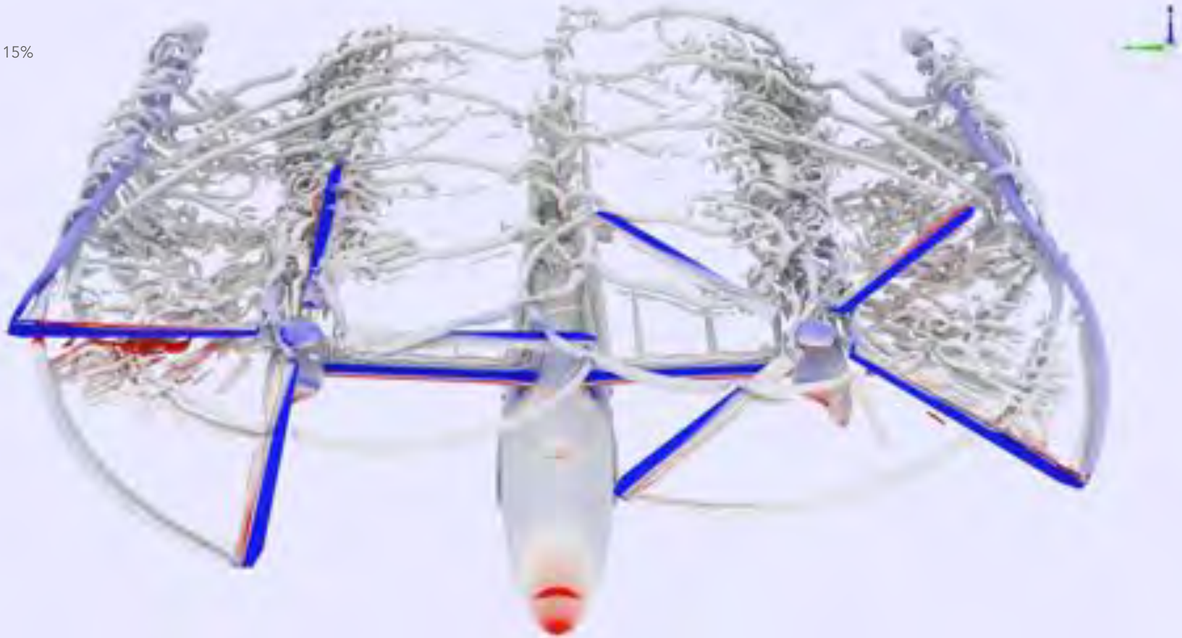


15%



Motivation: Overlapped, side-by-side rotor performance in cruise is better than separate non-overlapped rotors:

- *The combined wake system approximates that of a single wing with a large span, which reduces the induced power.*

Objectives: Study the aerodynamics and performance of NASA's side-by-side UAM concept:

- *High-fidelity CFD loosely coupled with rotorcraft comprehensive analysis.*
- *The tools developed can be used to explore the noise and performance for different configurations of multi-rotor UAM vehicles in support of eVTOL air taxi operations.*

"The Side-by-side Urban Air Taxi Concept",
P. Ventura Diaz, W. Johnson, J. Ahmad and S. Yoon, AIAA Paper 2019-2828

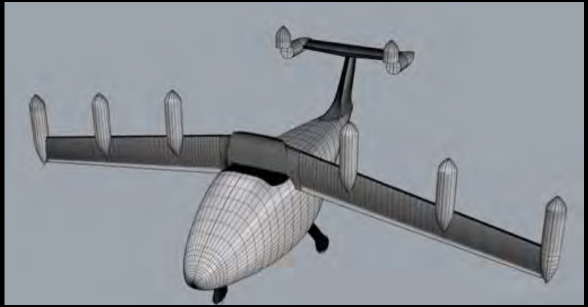
Tiltwing air taxi

Two different CAD geometries

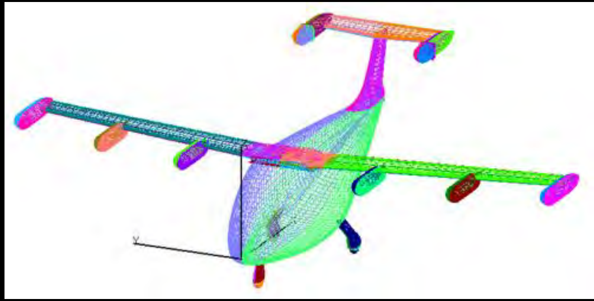
Airplane mode

"Airplane mode" geometry is used for cruise, no wing/fuselage gap

Helicopter mode

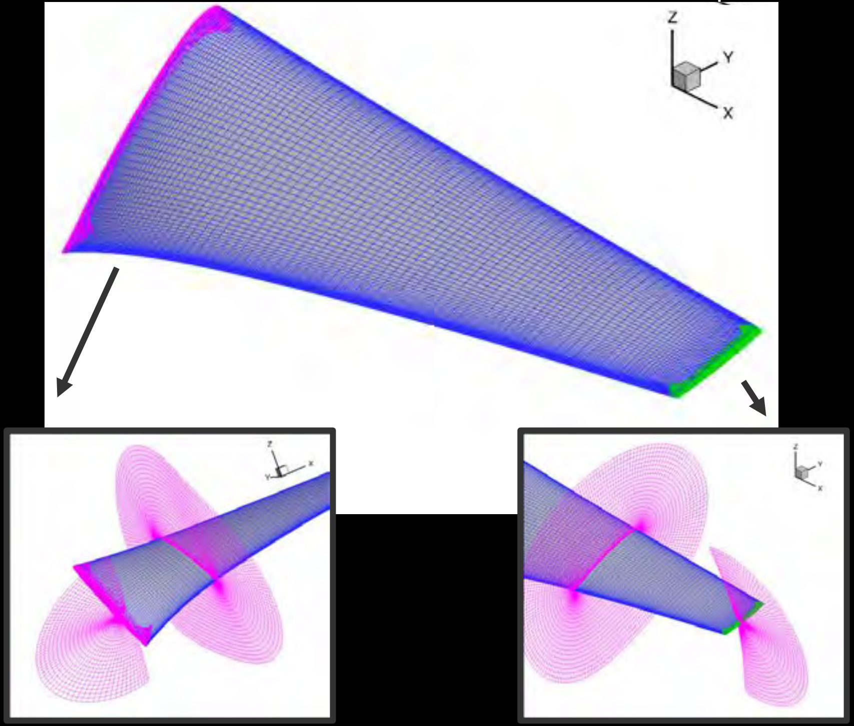


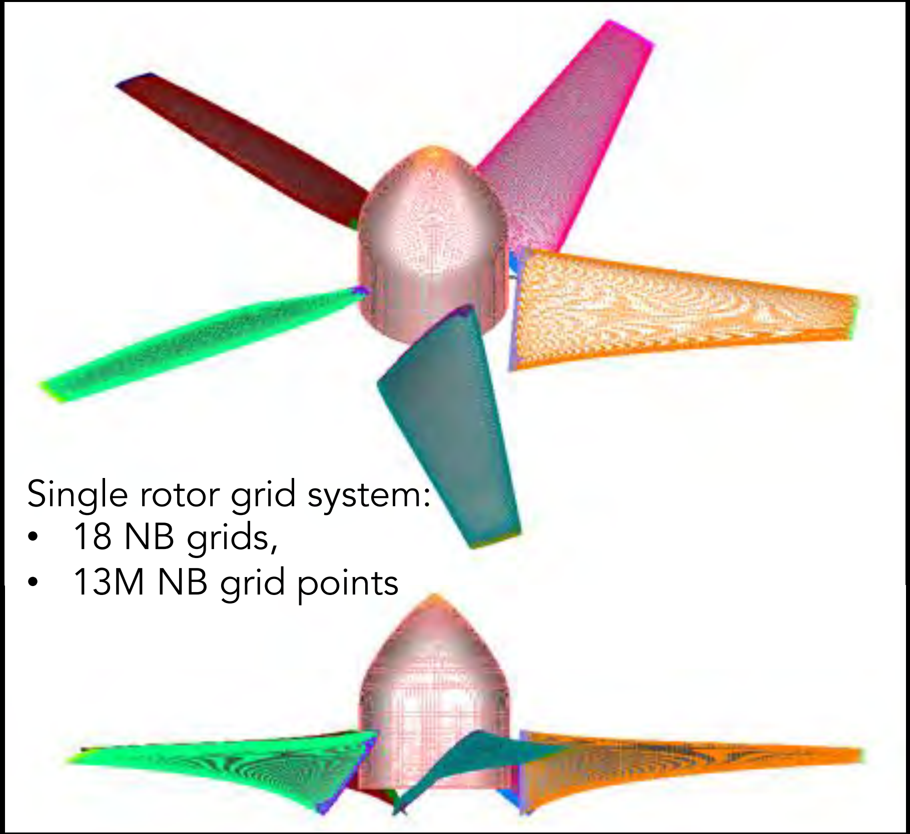
"Helicopter mode" geometry is used for hover/transition



Tiltwing air taxi

- VR12 airfoils from r =0 to r =0.85R.
- SSCA09 airfoils from r =0.95R to the tip, r = R.

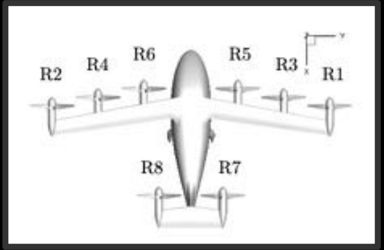


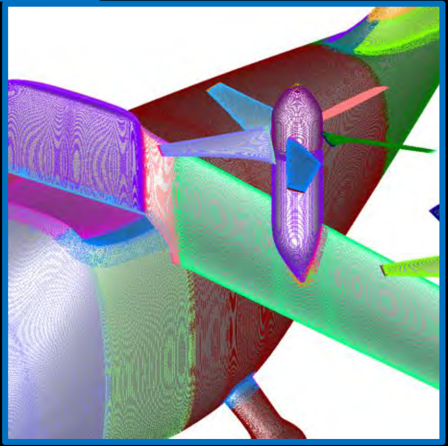


Single rotor grid system:
- 18 NB grids,
- 13M NB grid points

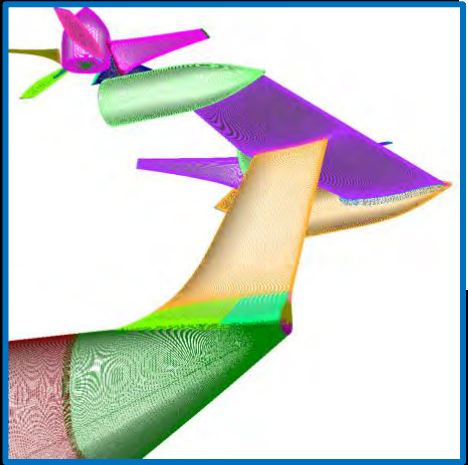
Tiltwing air taxi

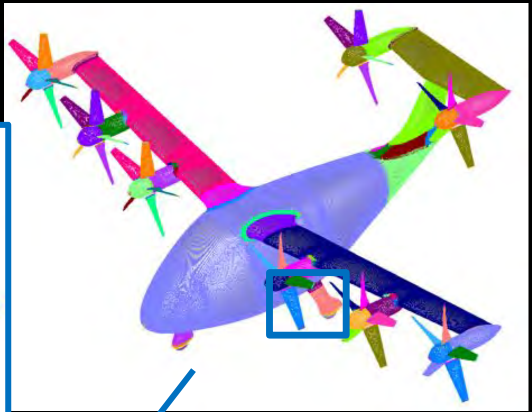
252 near-body grids
417M grid points



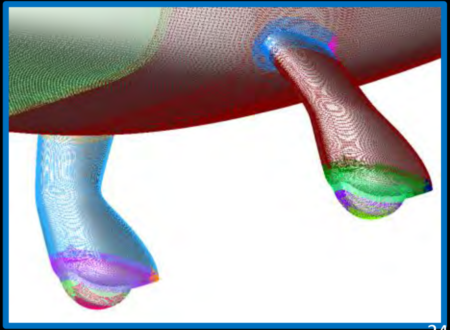


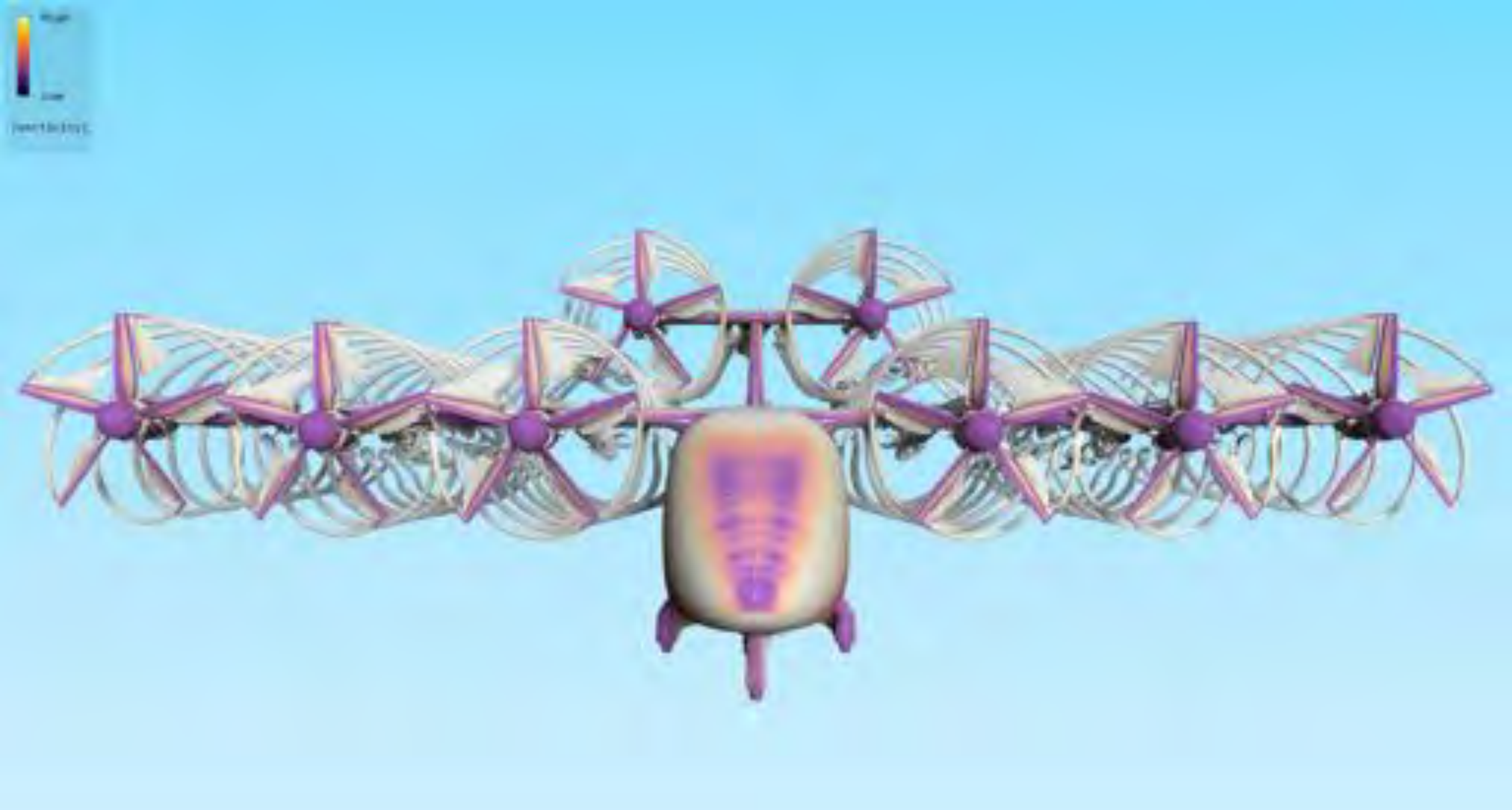
Most complex UAM concept to date that has been simulated with blade-resolved blades.



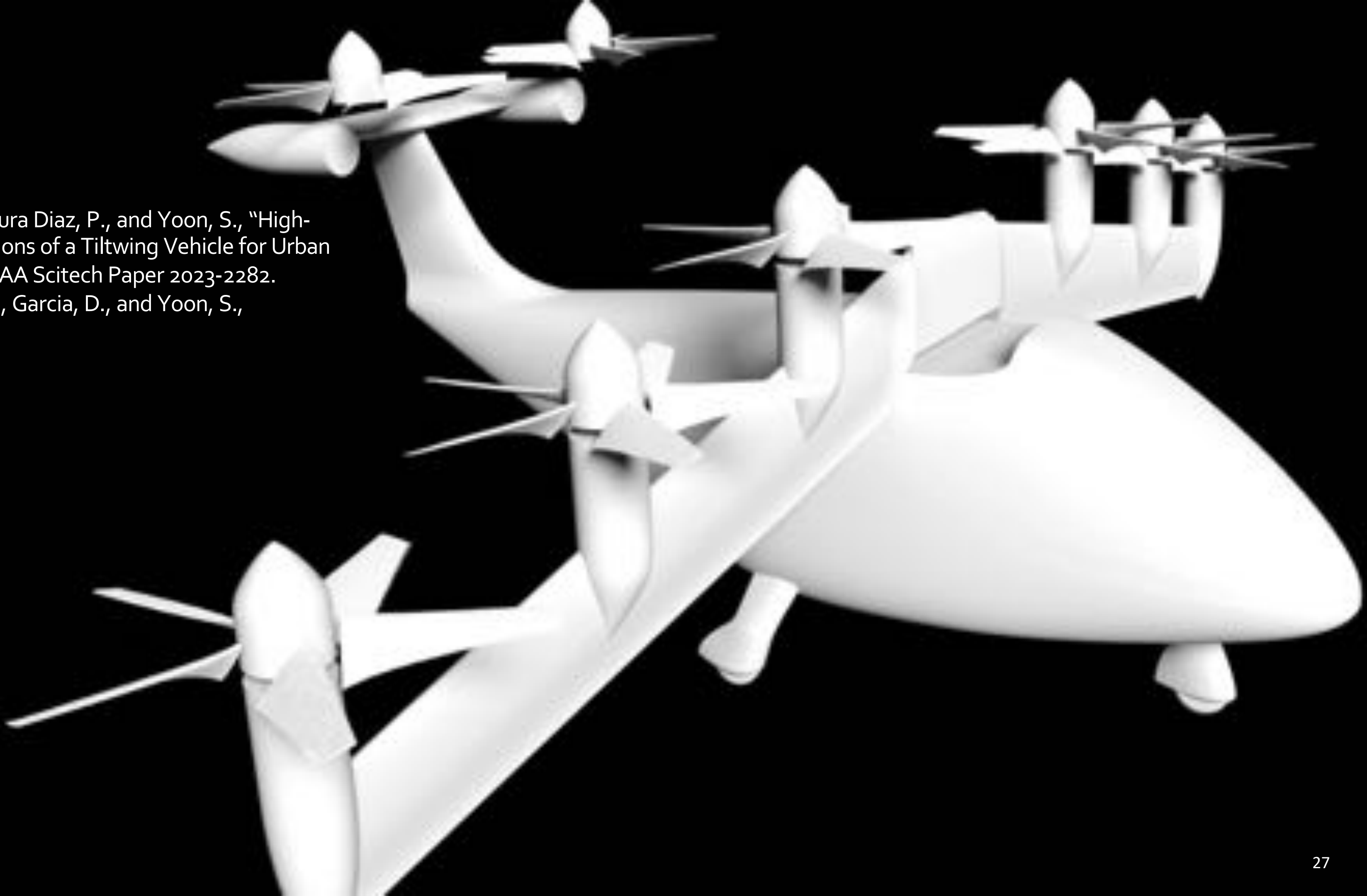


241 near-body grids
420M grid points

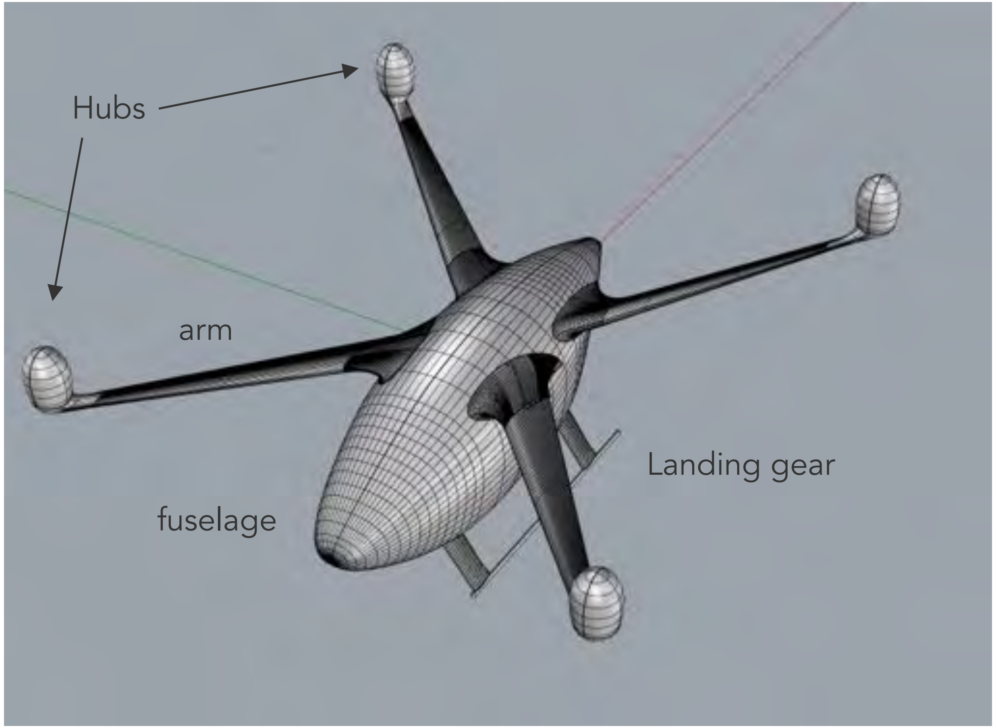




Garcia, D., Ventura Diaz, P., and Yoon, S., “High-Fidelity Simulations of a Tiltwing Vehicle for Urban Air Mobility”, AIAA Scitech Paper 2023-2282.
Ventura Diaz, P., Garcia, D., and Yoon, S.,

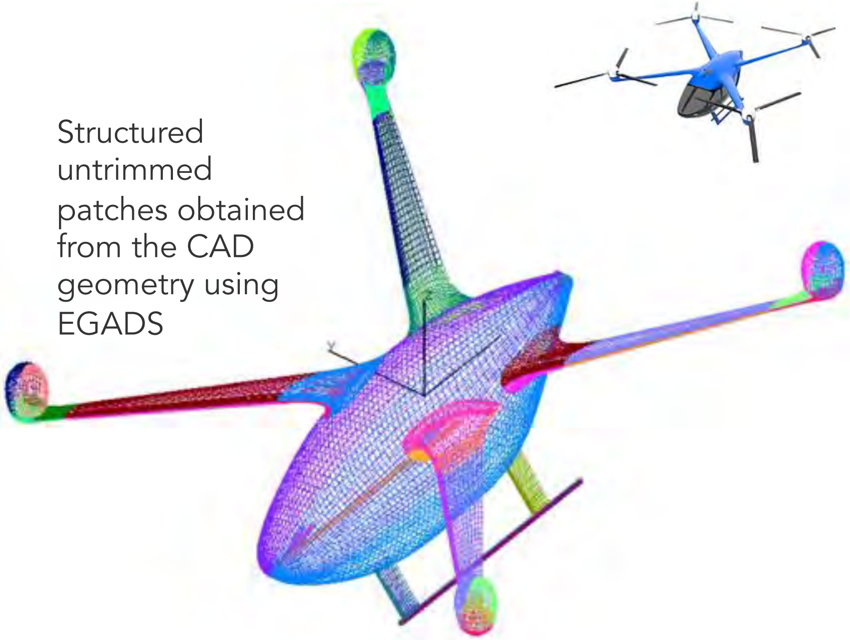


Quadcopter air taxi



Boundary Representation (BRep)

Structured untrimmed patches obtained from the CAD geometry using EGADS



Vertical separation between front and rear rotors to reduce rotor-rotor interactions in cruise, and decrease power required for forward flight [1]

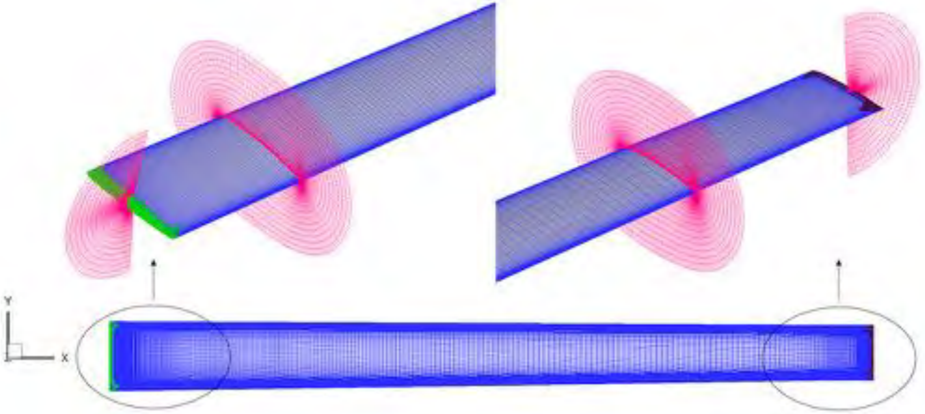
[1] Ventura Diaz, P., and Yoon, S., "High-Fidelity Computational Study of NASA's Quadrotor Urban Air Taxi Concept" AIAA Paper 2020–0302.

Quadcopter air taxi

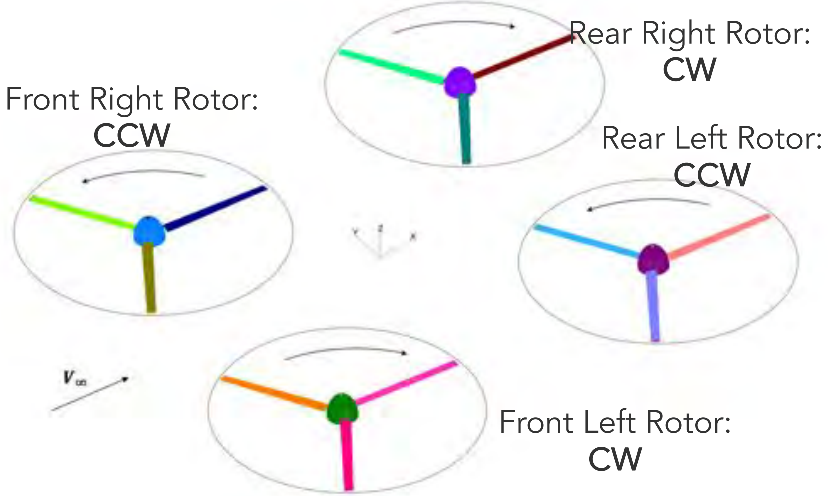
Rotor Geometry

- VR12 airfoils from r =0 to r =0.85R.
- SSCA09 airfoils from r =0.95R to the tip, r = R.
- The transition between the two different airfoil sections is smooth (linear interpolation with radial station).
- Linear sweep.

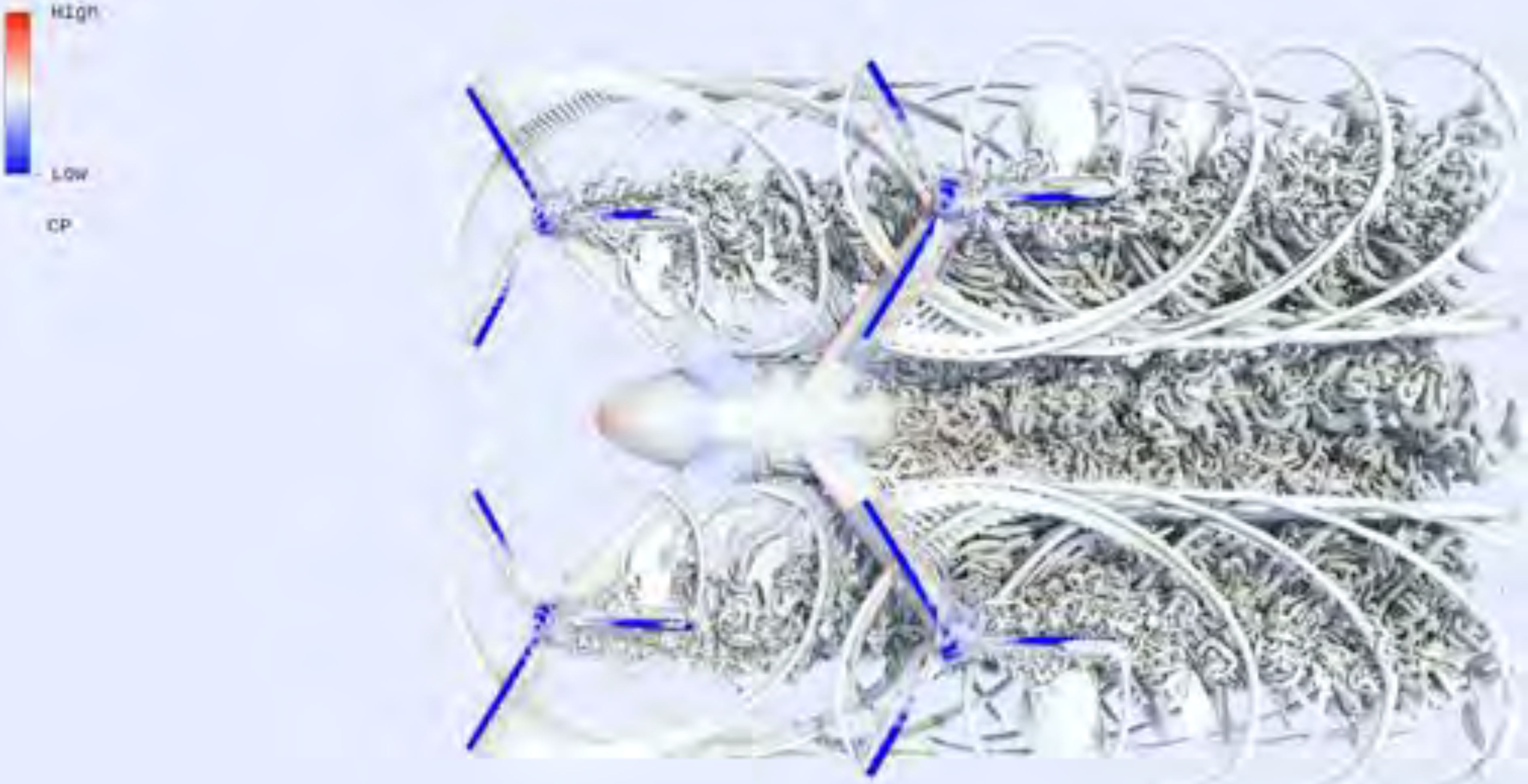
Rotor Number	Rotation	x	y	z
Rotor 1	CCW	$-1.35R$	$1.35R$	$0.25R$
Rotor 2	CW	$-1.35R$	$-1.35R$	$0.25R$
Rotor 3	CW	$1.35R$	$1.35R$	$0.6R$
Rotor 4	CCW	$1.35R$	$-1.35R$	$0.6R$



Single blade overset surface and NB volume grids



Quadrotor “rotors-only” overset surface grids



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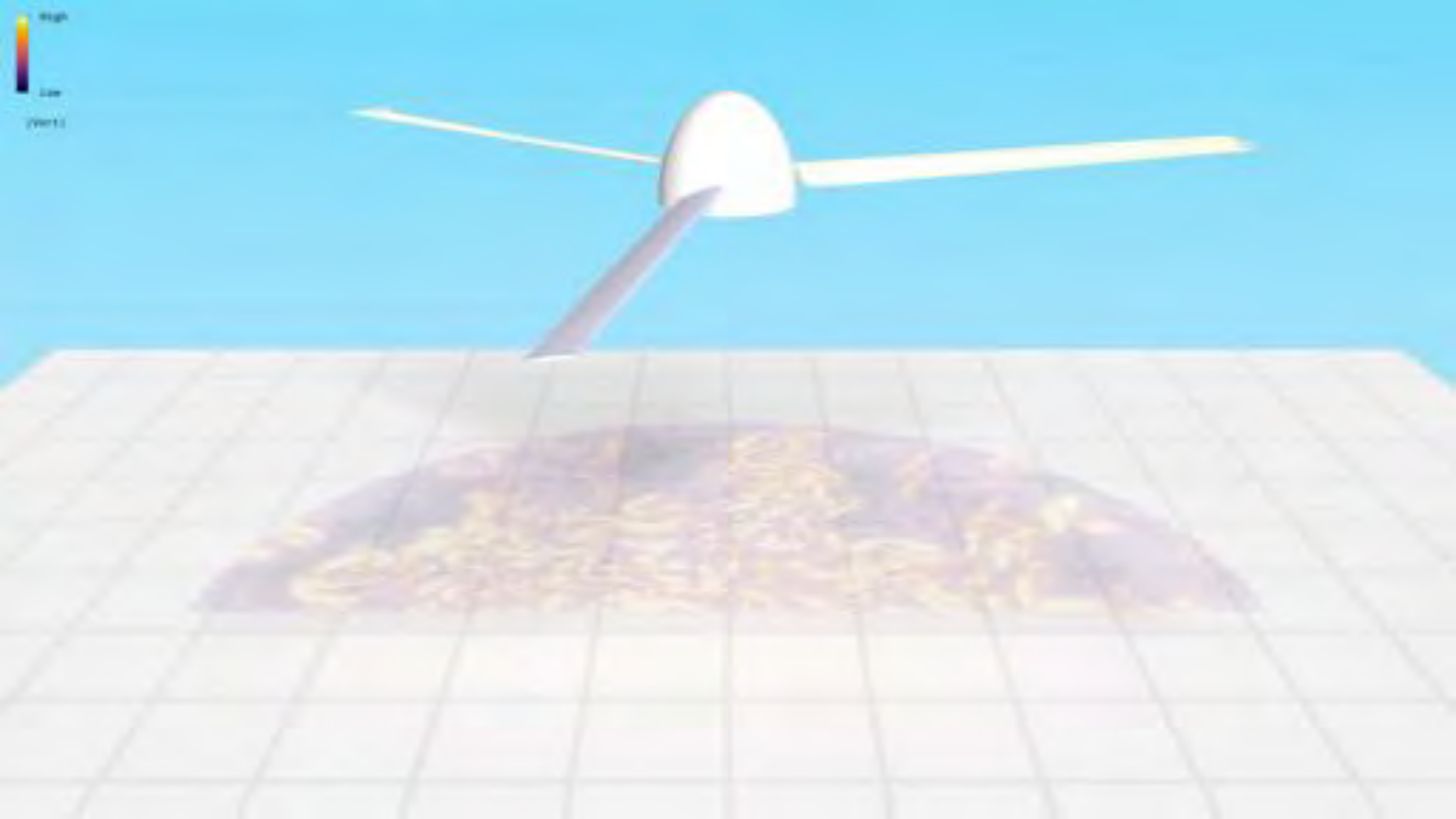
High
Low

Summary and Acknowledgements

SUMMARY

- NASA's air taxi UAM concepts have been analyzed using overset grids, comprehensive tools and high-fidelity Computational Fluid Dynamics (CFD).
- High order accurate CFD is the right tool to understand, analyze and visualize the complex flows in multi-rotor vehicles.
- NASA's air taxi concepts are designed to focus and guide NASA research activities in support of aircraft development for emerging aviation markets, in particular VTOL activities

ACKNOWLEDGEMENTS

- This work was supported by the RVLT project (Noah Schiller, PM; Brian Allan, PI).
- Timothy Sandstrom for his state-of-the-start flow visualizations
- The computations utilized the Pleiades, Electra, and Aitken supercomputers at the NASA Advanced Supercomputing (NAS) Division.

Questions?