Multi-Disciplinary, Physics-Based simulation and a Paradigm Shift in Defense Aircraft Acquisition

DOD HPC MODERNIZATION PROGRAM

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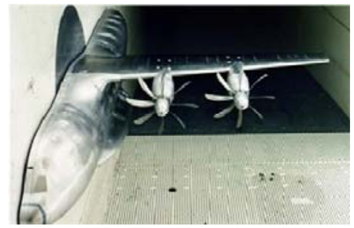
- The author is indebted to the highly skilled and dedicated members of the several CREATE-AV software development teams. It is a rare honor to work with such an outstanding group of individuals.
  - ✓ Quality Assurance Group
  - ✓ Pilot Projects Group
  - ✓ 3 Multi-Disciplinary, Physics-Based Simulation Software Development Groups
    - DaVinci (Conceptual Design software)
    - Helios (High-Fidelity Rotorcraft Simulation software)
    - Kestrel (High-Fidelity Fixed-Wing Simulation software), which includes our propulsion group for both Helios and Kestrel.

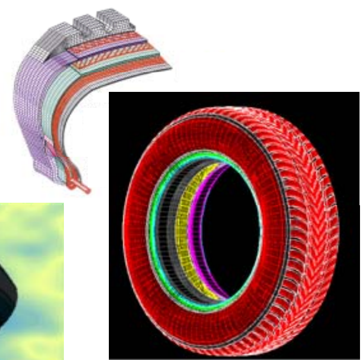
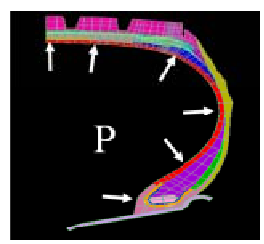
- **Existing DoD paradigm** (design, build, test, fix…)





Requirements → Design → Scale-Model Tests → Full-Scale Tests → Production

- **Goodyear "Innovation Engine"** (design, virtual test, fix, build, deploy)

Inflation and Seating



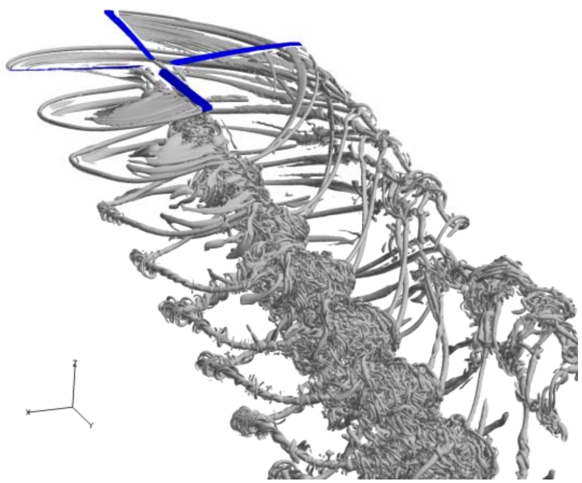
Flight Radial

Requirements → Design & Mesh Virtual Product → Analyze & Test Virtual Product → Build & Test Physical Product → Market

Design iterations

A Paradigm Change for Acquisition of Air Vehicles

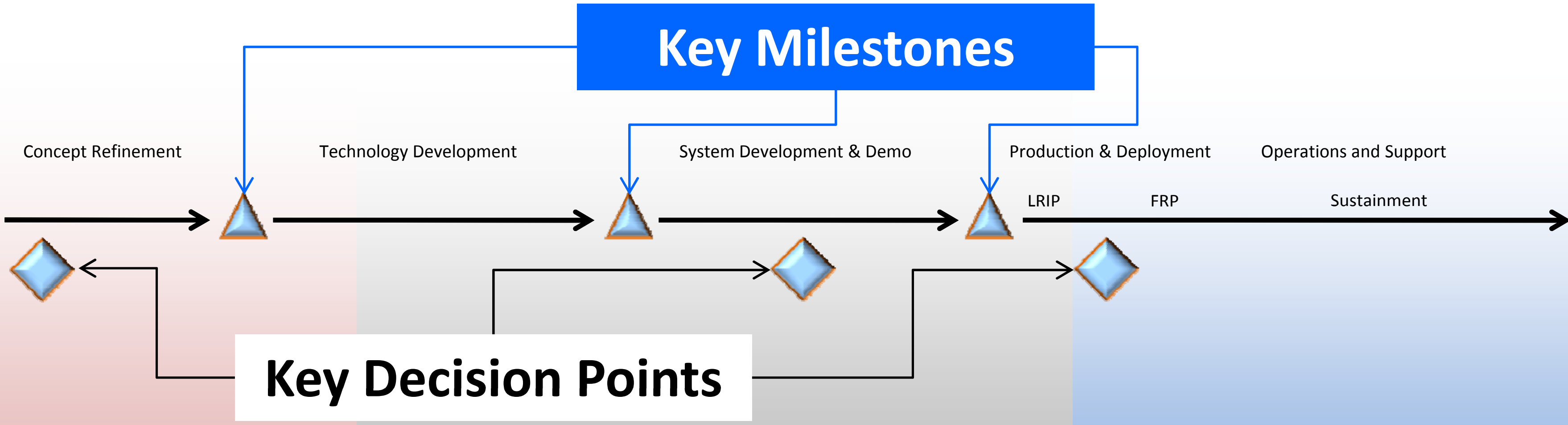
- **Multi-disciplinary, physics-based software** and next-generation HPC systems **enables full-vehicle "virtual test" capacity** – the key to a paradigm shift in aircraft acquisition.



ERF 2011, Paper 148, Potsdam, et al.

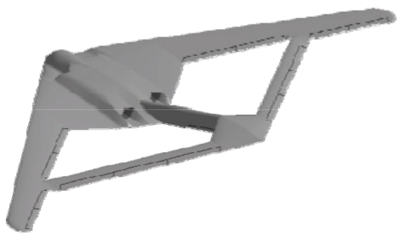
- **Enabling Use Cases…**
  - ✓ Design verification prior to key decision points (and prior to fabrication of test articles or full-scale prototypes)
  - ✓ Evaluation of planned or potential operational use scenarios
  - ✓ Planning/rehearsal of wind-tunnel and full-scale flight tests
  - ✓ Performance of flight certifications (e.g., airworthiness, flight envelope expansion, …)
  - ✓ Calibration of low-fidelity analysis tools associated with conceptual design

Aircraft Acquisition



- **Requirements**
- **Concept Refinement**
- **Technology Development, e.g.**
  - ✓ Reliability & Maintainability Assessments
  - ✓ Aerodynamic Force Accounting Processes
- **System Development & Demonstration, e.g.**
  - ✓ Fabrication of scale models and full-scale prototypes
  - ✓ Airframe/Propulsion System Integration Processes
- **Production and Deployment, e.g.**
  - ✓ Low rate initial production
  - ✓ Full rate production
- **Operations and Support, e.g.**
  - ✓ Airworthiness Certifications
  - ✓ Discovery of System Deficiencies
  - ✓ Mishap Investigations
  - ✓ Launch & Recovery Envelope Generation Processes
  - ✓ Up and Away Envelope Expansion Processes
  - ✓ Modified/New Configuration Certifications
  - ✓ Repair/Damage Assessments

- **Conceptual Design**



Physics-based simulation can play an important role in assessing impacts of key performance parameters on vehicle capability, cost, and technical risk at the earliest stages of acquisition.

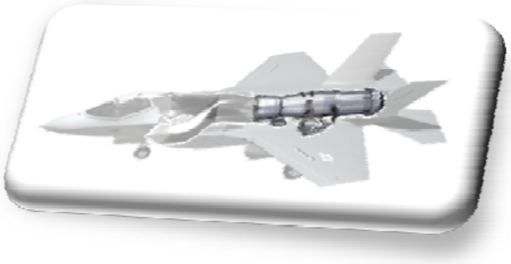
- ✓ DESIGN – thousands of systems (w/ system design generation tools) to create, explore, and understand a rich design space.
- ✓ ANALYZE – hundreds of system designs using physics-based analysis tools, adding to and refining the knowledge captured in design space exploration.
- ✓ OPTIMIZE – use knowledge gained from DESIGN and ANALYSIS activities to perform cost, schedule, risk, performance, and effectiveness trades to find a set of preferred system solutions.

Cycle-time for early-phase acquisition engineering processes is generally VERY short.

- **Airframe Propulsion System Integration**
(High payoff potential for virtual airframe propulsion system integration testing)

http://www.youtube.com/watch?v=16ti9GwnlVs&feature=related

- **Currently, component mating does not occur until late** in the development cycle (i.e. flight tests) which may not occur for 15-20 years after concept development.

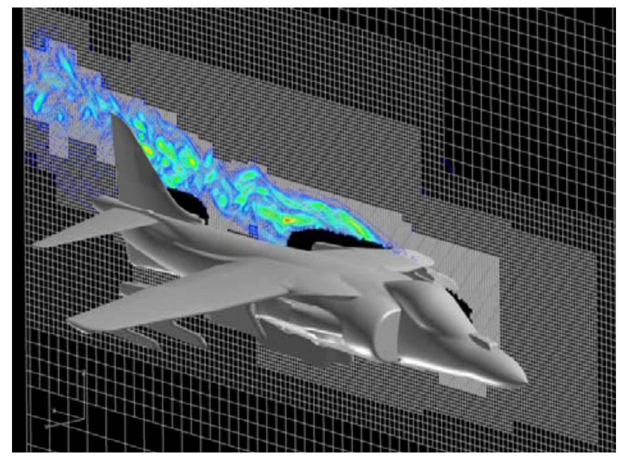


- **Discovery of System Deficiencies**. Potential exists for physics-based simulation to identify, evaluate, and implement necessary corrective actions on discovery of a system defect during operational use or flight tests. Cycle time can be very short for safety of flight issues. More significantly, it is possible to discovery system deficiencies early in the design process (prior to fabrication) through physics-based virtual testing.

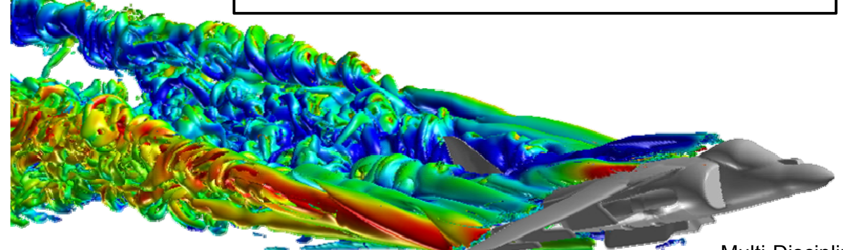
- **F-18 High Alpha Research Vehicle (HARV)**

http://www.youtube.com/watch?v=9fspStedQCg

- **AV-8B Vortex/Tail Interactional Dynamics**



AIAA 2011-1108, Hariharan, et al.



- **Launch and Recovery Envelope Generation Process**
  Potential exists for physics-based simulation to generate wind-over-the-deck launch and recovery flight envelope that defines limits of safe aircraft/ship operations. Envelope currently generated through flight test, w/ pilot flying aircraft to ship in increasingly severe conditions until limit ID'd. Envelope also limited by environmental conditions on day of test.

- **Lynx helicopter operational envelop definition**
  (virtual testing and risk reduction)

http://www.youtube.com/watch?v=bC2XIGMI2kM

The Vision for Physics-Based Simulation

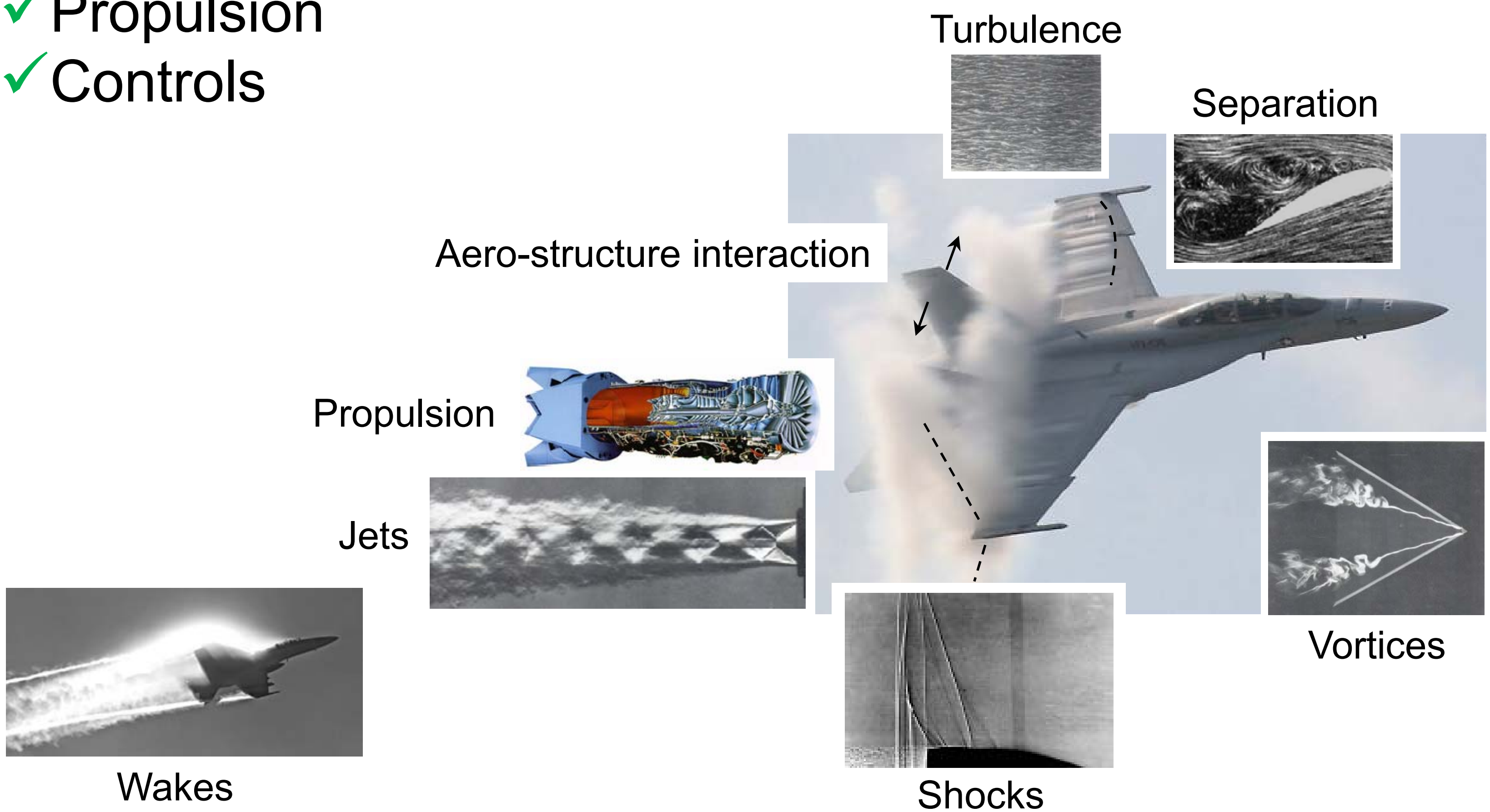
- **Physics-Based Simulation enables…**
  - ✓**Increased capacity** of the engineering workforce
  - ✓Reduced workload through **streamlined and more efficient engineering workflows**, and
  - ✓**Minimized need for rework** due to early detection capability of design faults or performance anomalies.
  - ✓**Decreased time to deployment** through reduced design cycle time.

- **Vision is NOT** the pitting of the traditional physical test paradigm against the capacity of physics-based simulation.

- **Vision IS** that the combination of multi-disciplinary, physics-based simulation with traditional means of generating engineering data, represents an opportunity to fundamentally change the paradigm for aircraft acquisition.

Present Scope for Air Vehicles

- **Scope of full-vehicle physics-based simulation**
  - ✓ Aerodynamics
  - ✓ Structural Dynamics
  - ✓ Propulsion
  - ✓ Controls



CREATE-AV Software Products

High-Fidelity design verification tool for FIXED-WING aircraft

High-Fidelity design verification tool for ROTARY-WING aircraft

Propulsion module delivers…
- GTE effects capability via Kestrel, Helios, & DaVinci
- High-Fidelity GTE simulation capability via Kestrel & Helios

Conceptual Design tool

Cadence of Software Development

Governance model for making technical decisions

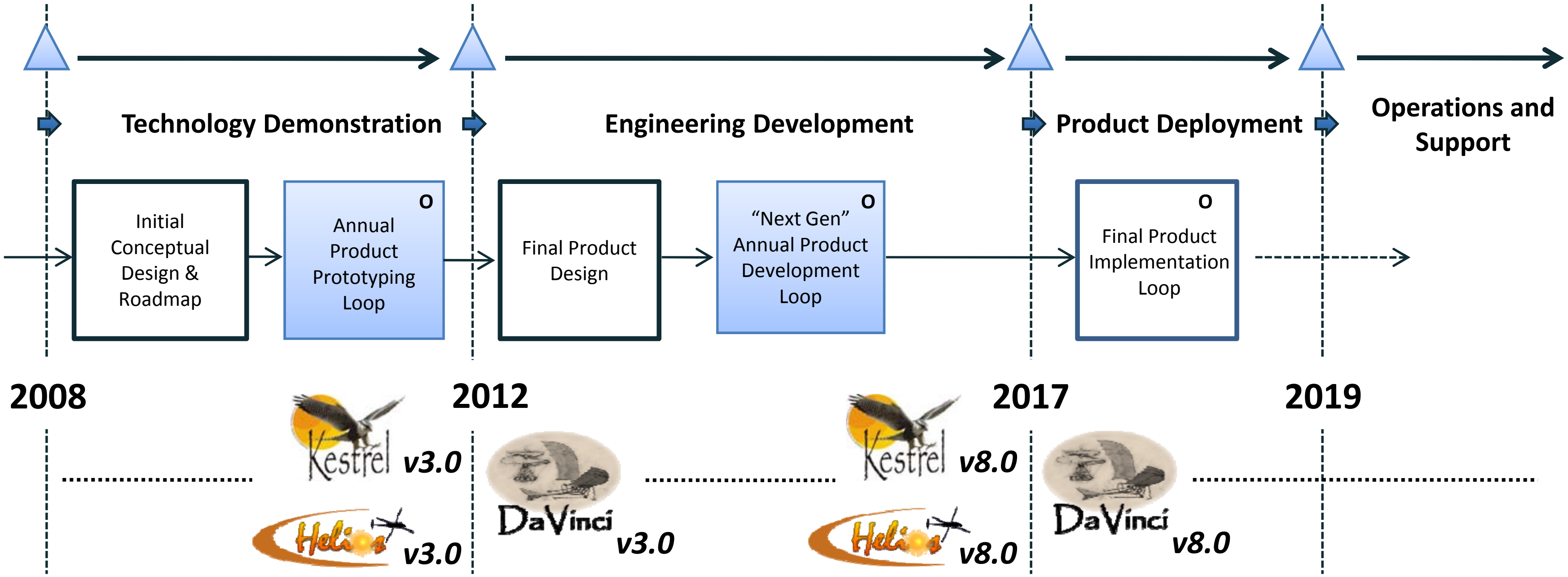
ANNUAL Product Development Milestones

F M A M J J A S O N D J F

Feb	Complete General Release	– Version N-1
Feb	Complete PDR	– Version N
Apr	Complete FDR	– Version N
Apr	Complete Product Branch	– Version N
May	Complete Integration	– Version N
Jun	Reconcile Requirements	– Version N+1
Sep	Freeze Release	– Version N
Oct	Complete Alpha Testing	– Version N
Nov	Complete Quality Assurance Test (QAT) Release	– Version N
Jan	Complete Beta Release	– Version N
Feb	**Complete General Release**	**– Version N**
Feb	Declare End of Life for Release	– Version N-2
Feb	Complete PDR	– Version N+1

Stages of Software Development

ANNUAL release cycle – increasing functionality, physical accuracy, computational efficiency, usability



Deploy to targeted government workforce for **DoD owned** acquisition engineering processes. **Engage industry via technical advisory boards and professional societies.**

Expand industry involvement via Beta-test events

Full deploy to government and industry for DoD acquisition engineering

An Observation

Frameworks versus Infrastructures

Both offer compelling development and maintenance advantages for multi-physics software products, but differ in method of delivery. It is important to recognize that the choice of one over the other is a development decision (as opposed to a *management* decision).

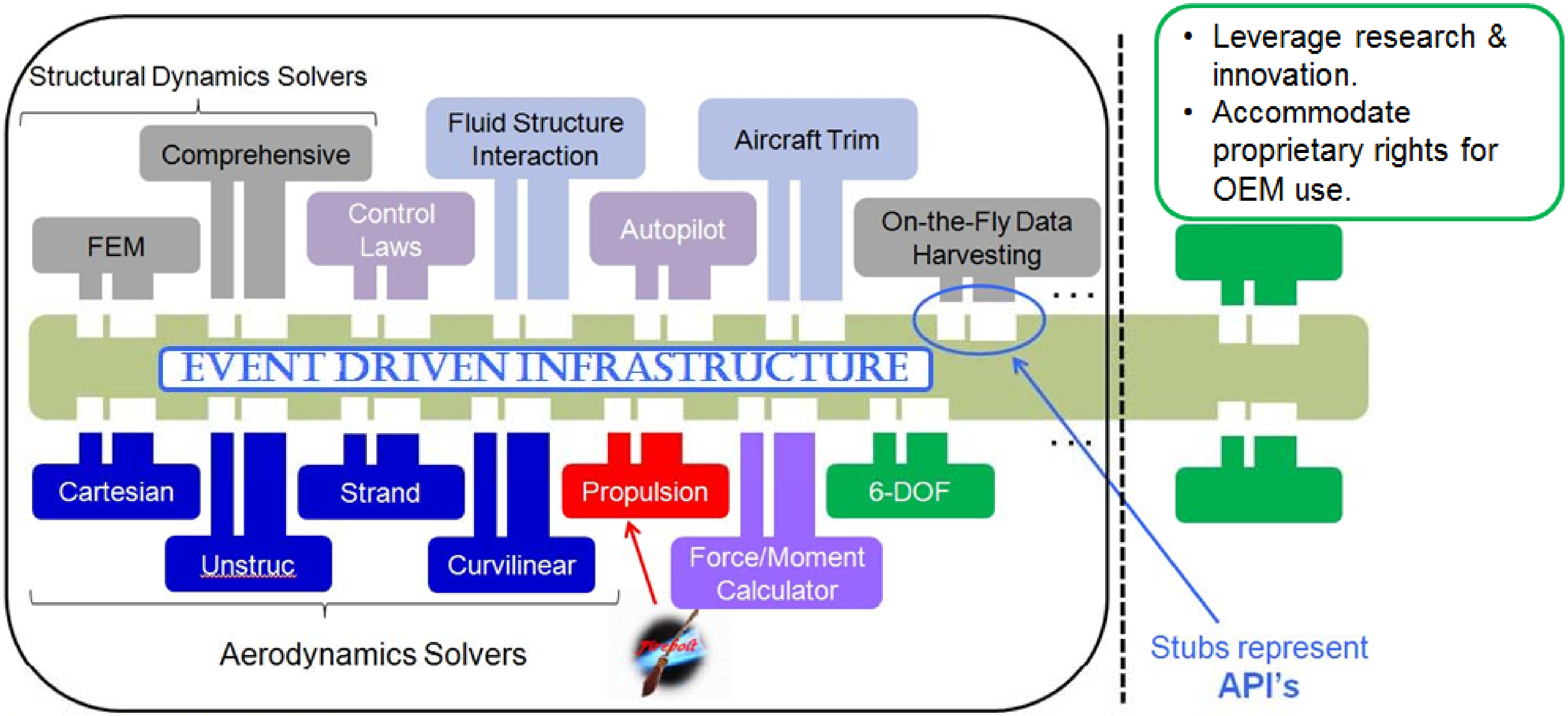
Both are intimately intertwined with the multi-disciplinary, physics-based nature of the product.

Framework: written to be GENERIC to meet diverse needs and are shared by multiple software products.

Infrastructure: developed for single product and target specialized needs.

Given the targeted long-life and operational constraints on CREATE-AV products, an "infrastructure" path has been chosen by our principal developers.

Common Scalable Infrastructure



Maintainable, Efficient, Agile

- Enables significant growth in Use Cases with no modification to source.
- All component APIs & data structures consistent across project (reduced development cost).
- Enables software maintenance over time.

Defense Acquisition and Actionable Engineering Data

- Must be available when it is needed (Timeliness)

  Can tool deliver actionable engineering data when it is needed?

- Correctly represent the governing physics (Physical Accuracy)

  Can the tool deliver engineering data of sufficient physical accuracy to be actionable?

- Must be of quantifiable quality (Uncertainty Quantification)

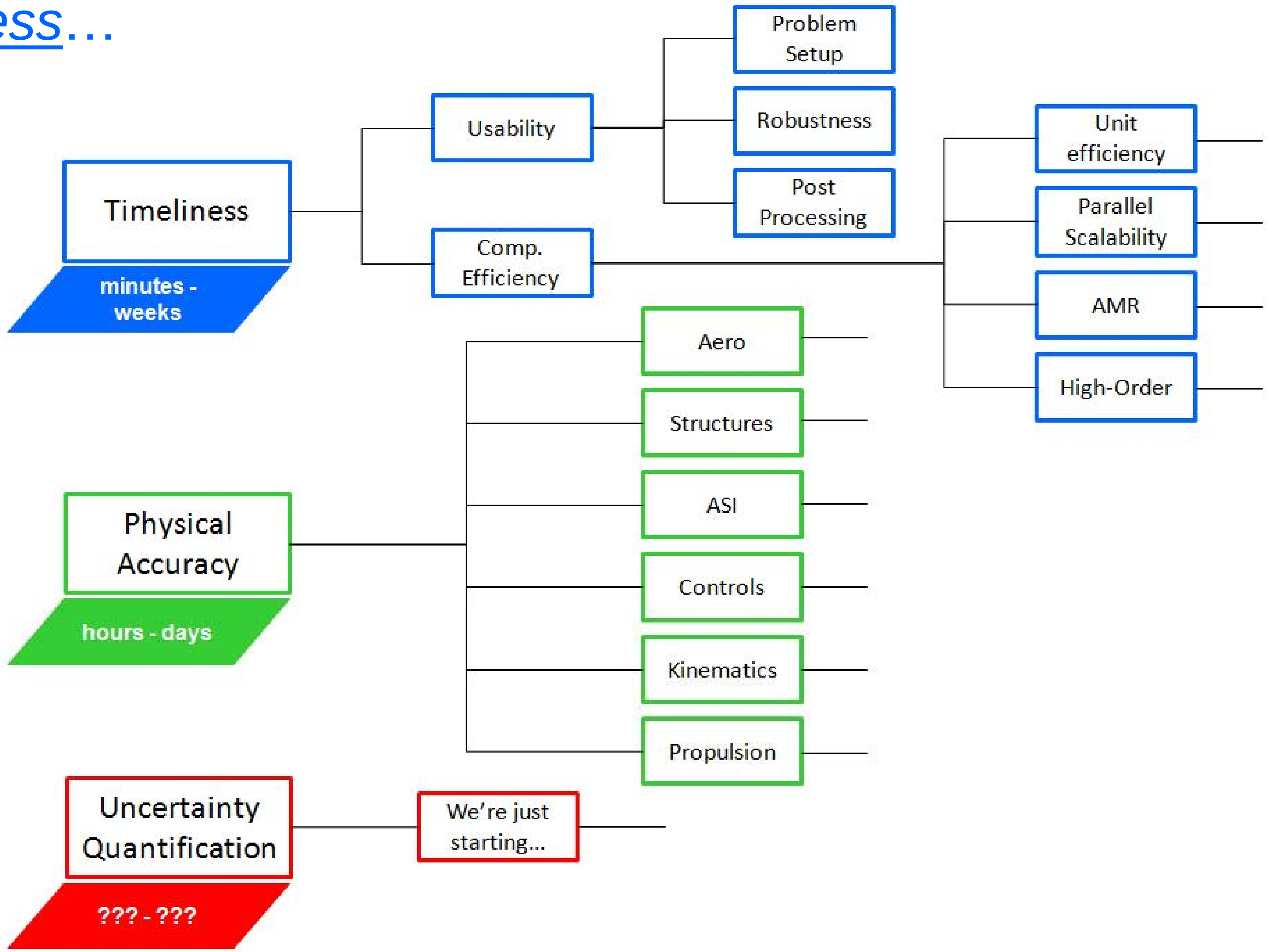
  How far can decision maker rely on the data? If there is anything wrong with the data, how will the decision maker know it?

Paths to Envisioned Mature State

- What is currently the most limiting technology area relative to progress toward the envisioned mature state of multi-disciplinary physics-based simulation for aircraft acquisition?

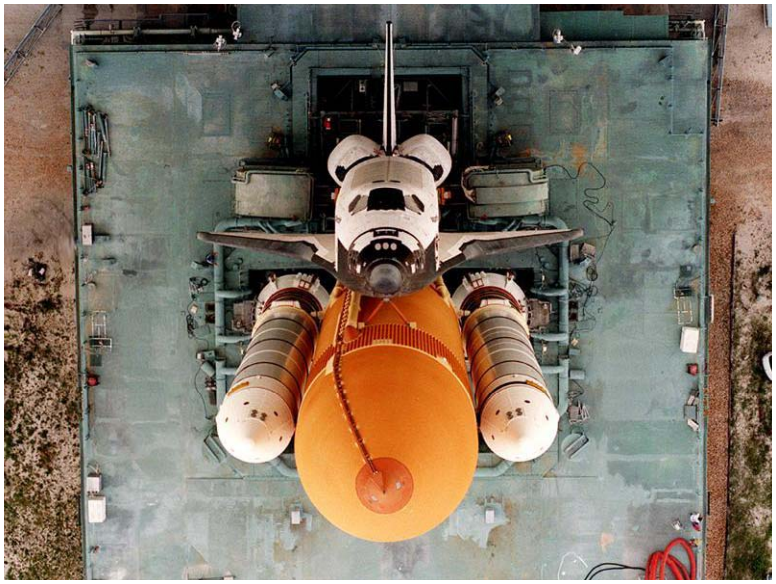
We want to have impact on decisions across the acquisition spectrum (conceptual design through sustainment)

- Timeliness, physical accuracy, and uncertainty quantification are ALL essential to make effective programmatic decisions, *but if one had to choose the most important, perhaps it would be* ***timeliness***…



Timeliness

- **An Example…**
  Scheduled pause in countdown to assess system readiness



System readiness data unavailable at decision time…

- ✓ Launch (if decision maker considers risk of missing data to be small)
- ✓ Delay (await analysis and possibly the next launch window)

A lack of timeliness associated with engineering data always has the effect of increasing risk and causing programmatic delays.

(risk and delay both translate to $)

Timeliness Decomposition

- **Usability**
  - ✓Problem Setup
    - Geometry creation/repair
    - Aerodynamics
      - mesh generation
      - case/scenario definition
    - Structural dynamics
      - mesh generation
      - material properties & definitions
  - ✓Post Processing
    - data analysis
    - report preparation
  - ✓Robustness

    Robustness implies that software can be used effectively by practicing engineers (rather than developers) with minimal training (e.g., 1-week short course, tutorials, user guides, etc) – as opposed to years of experience.

- **Computational Efficiency**
  - ✓Basic algorithm efficiency
  - ✓Parallel efficiency & scalability
  - ✓Memory use

Computational Efficiency	CURRENT Time Requirement
Full Vehicle Simulations*	**Hours – Days**
Aerodynamics – high fidelity	
Structural Dynamics – modal (fixed-wing), non-linear FEM beams (rotor blades)	
Propulsion – 0D engine cycle deck	
Control Surface Movement (prescribed)	

* e.g., full fixed-wing configuration for simple maneuver w/ control surface movement and engine throttle adjustment; full helicopter configuration for 10's of revolutions of the main rotor; etc.

Usability	CURRENT Time Requirement
Problem Setup	
Geometry* repair (depends on state of CAD and experience of the engineer)	Hours – Days
Aerodynamics	
mesh generation (depends on experience of the engineer)	**Days – Weeks**
case/scenario definition	Minutes – Hours
Structural dynamics	
mesh generation	Minutes – Hours
material properties & definitions	**Minutes – Weeks**
Post Processing	
data analysis	Hours – Days
report preparation	Minutes – Hours

* Building geometry is a process. Here we assume that geometry is persisted throughout the design-cycle from conceptual design through detail design, FDR, and beyond.

Legend: (manual icon) = manual or interactive (gears icon) = automatic

Usability	CURRENT Time Requirement
Problem Setup	
Geometry* repair (manual)	Hours – Days
Aerodynamics	
mesh generation (manual)	Days – Weeks
case/scenario definition (manual)	Minutes – Hours
Structural dynamics	
mesh generation (automatic)	Minutes – Hours
material properties & definitions (manual)	Minutes – Weeks
Post Processing	
data analysis (automatic)	Hours – Days
report preparation (manual)	Minutes – Hours

* Building geometry is a process. Here we assume that geometry is persisted throughout the design-cycle from conceptual design through detail design, FDR, and beyond.

- **What would it mean to our ability to impact important engineering processes throughout spectrum of acquisition if we could drop aero mesh gen cycle time to minutes/hours?**

- **How can we beat down the aero mesh gen bottle-neck?**

NOTE: Current problem setup time for new rotors (specification of material properties and structural definition) can rival that of mesh generation for aerodynamics. This process in not in our direct control (legacy tools required). In future development cycles, when high-fidelity structural dynamics simulation are accommodated, problem setup will build directly from geometry definition – for which mesh generation is already highly efficient and essentially automatic.

Automation of Mesh Generation for Aerodynamics Possible?

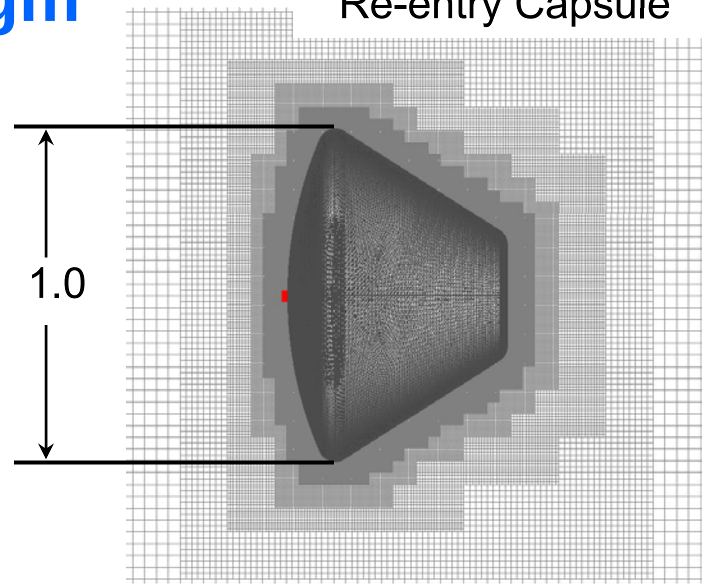
CREATE-AV Hi-Fi Products Adopt a Dual Mesh Paradigm

- **Why is it needed?**
  - ✓Discretize the computational domain
  - ✓Enable automation of volume mesh generation

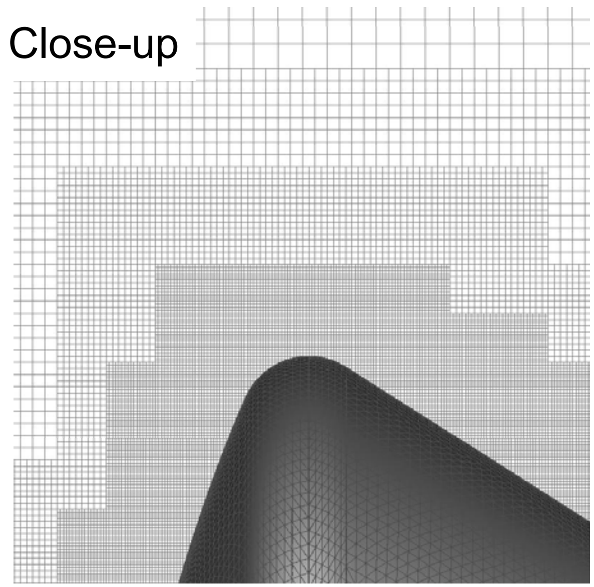
Ideally, we'd just use uniform Cartesian mesh(es) all the way to the wall. However, resolution required for viscous BL is prohibitive. Hence, strand mesh for near-body

Spacing Requirement*	Δ_{min}	N_{total}
NB/OB Transition	$1.0\text{x}10^{-2}$	$1.86\text{x}10^{+6}$
Inviscid Wall	$5.0\text{x}10^{-3}$	$5.89\text{x}10^{+6}$
Viscous Wall	$1.0\text{x}10^{-6}$	$8.43\text{x}10^{+12}$
* assumes Re = $2.5\text{x}10^{+6}$ and an AMR Factor = 2		

Re-entry Capsule



Close-up



Dual Mesh

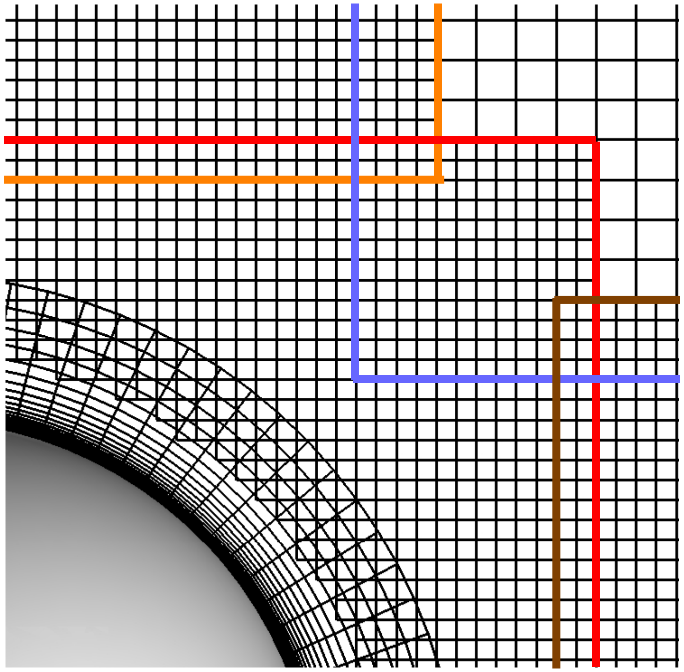
- **What is it?** AIAA 2008-0927, Wissink, et al.
  - ✓Decomposition of the computational domain into near-body and off-body partitions.

Off-Body

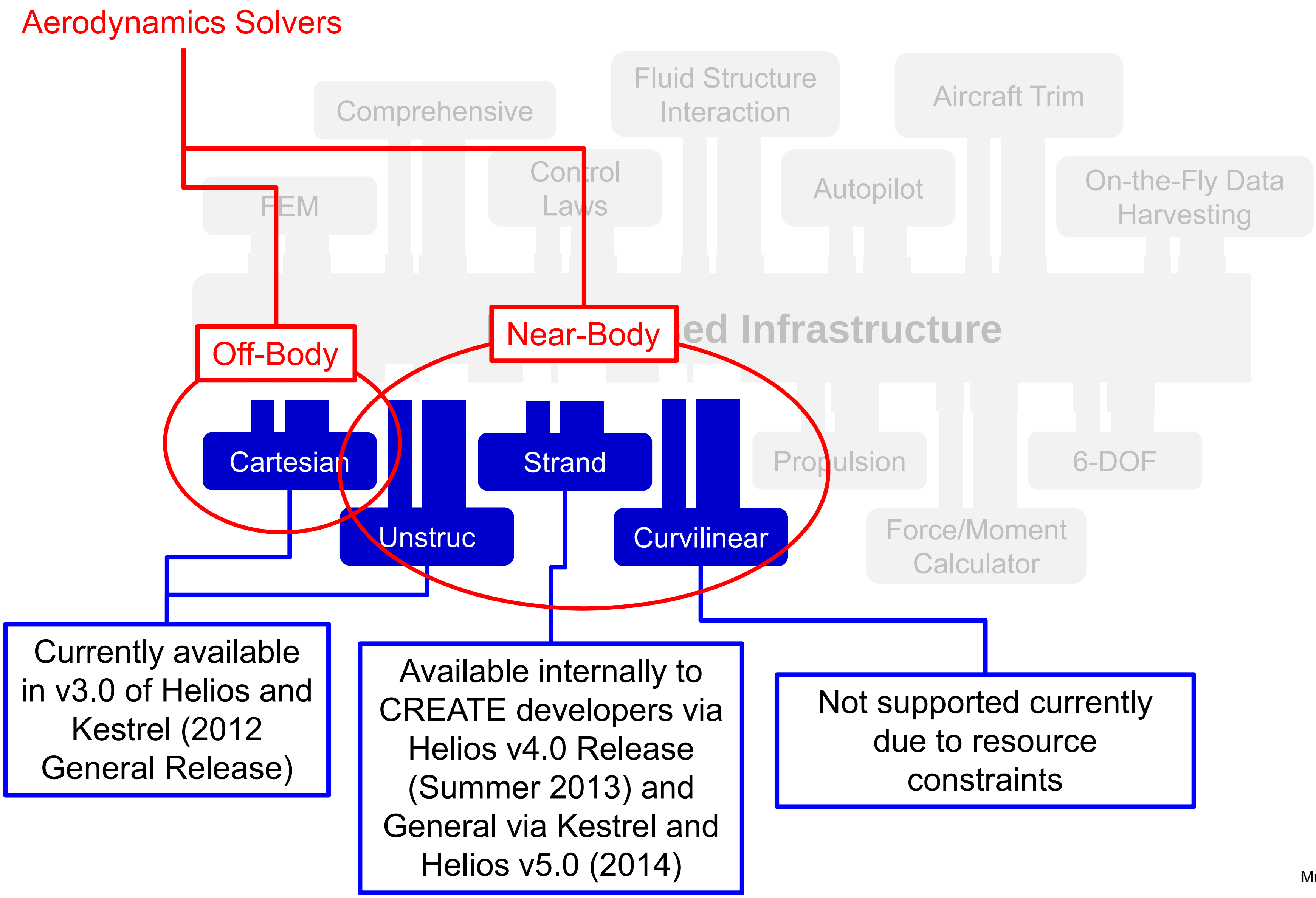
Nested uniform Cartesian mesh components w/ telescoping of refinement to insure compatibility w/ transitional spacing of strand mesh

Near-Body

Strand mesh

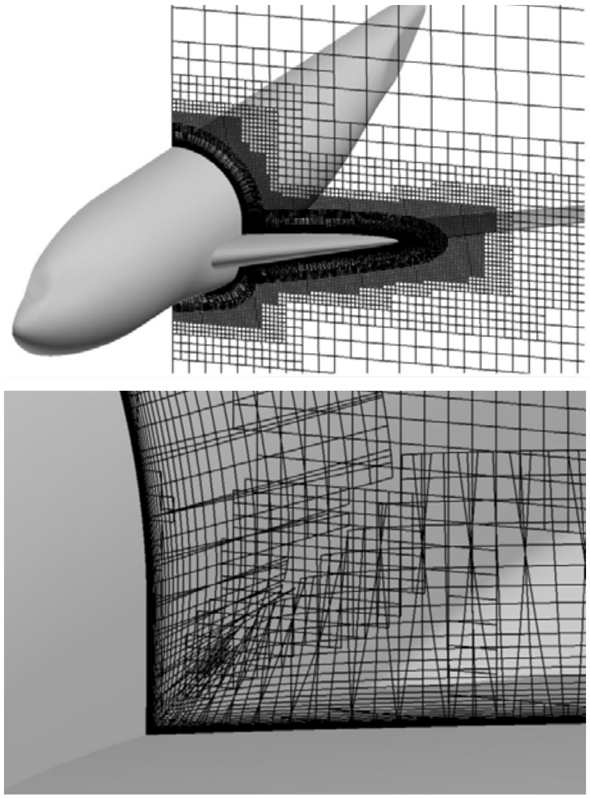


Supported Mesh Types

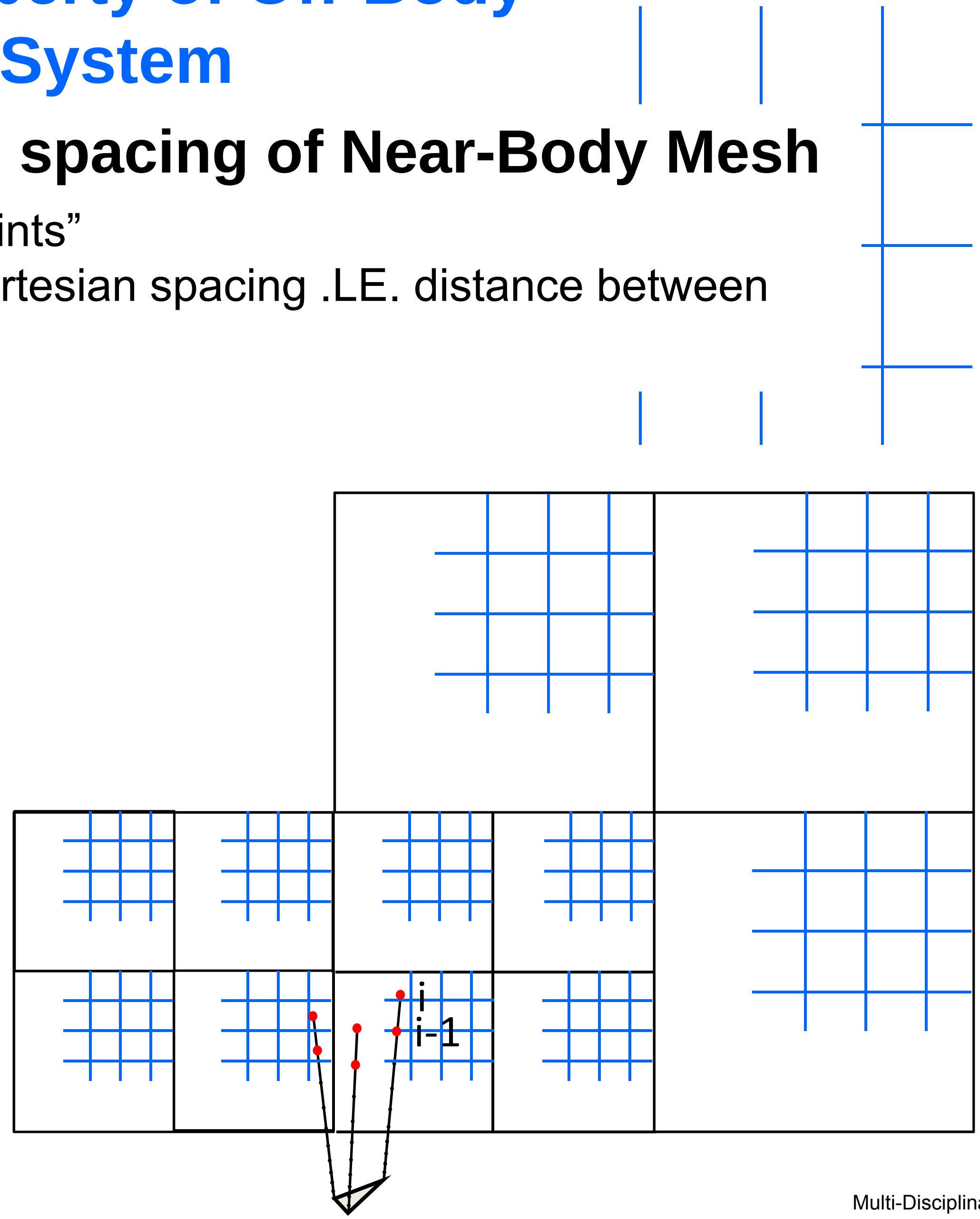


Telescopic Property of Off-Body Mesh System

- **Telescope to transitional spacing of Near-Body Mesh**
  - ✓ Refinement triggered by "clip points"
  - ✓ Refinement terminates when Cartesian spacing .LE. distance between clip point index (i) and i-1.



AIAA 2010-4934, Katz, et al.



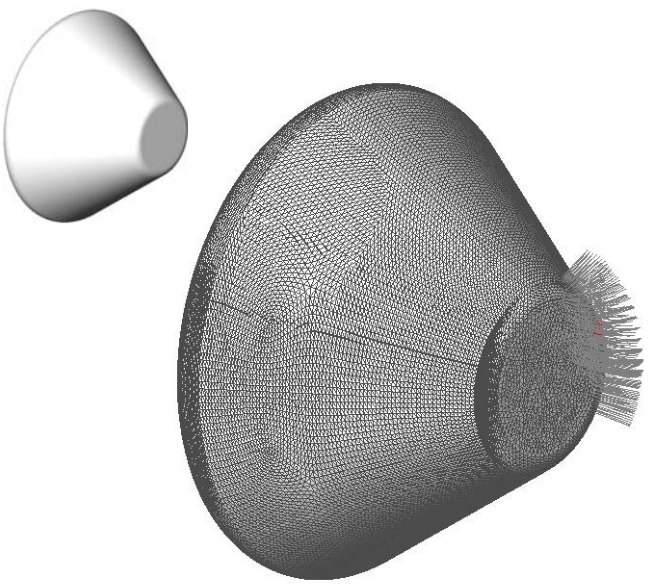
Advantages

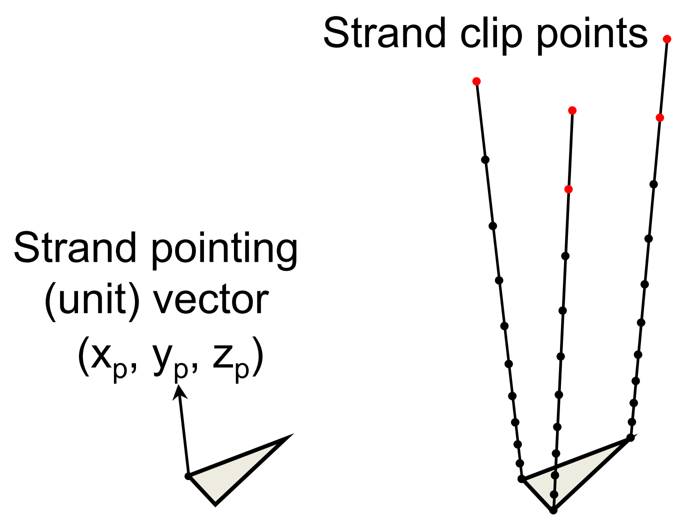
- **What are the advantages of nested Cartesian off-body system?**
  - ✓ Fully automatic mesh generation
  - ✓ Low memory for mesh related data (6 REALS and 1 INT per mesh component)
  - ✓ Enables fully automatic AMR in off-body domain
  - ✓ Insures resolution compatibility between off-body system and transitional spacing of near-body strand system
  - ✓ Enables simplest realizable implementations of numerical algorithms (e.g., AMR, multi-grid, high-order solvers, etc)

Strand Mesh and Path to Automation

(path to full automation for aero surface and volume mesh generation)

- **What is a Strand Mesh?** AIAA 2007-3834, Meakin, et al.
  - ✓Unstructured surface mesh (tri, quads, other…)
  - ✓Strand pointing (i.e., directional) vector
  - ✓Point distribution to resolve viscous boundary layer and transition to Euler spacing
  - ✓Requires use of "Dual Mesh" (near-body/off-body) paradigm

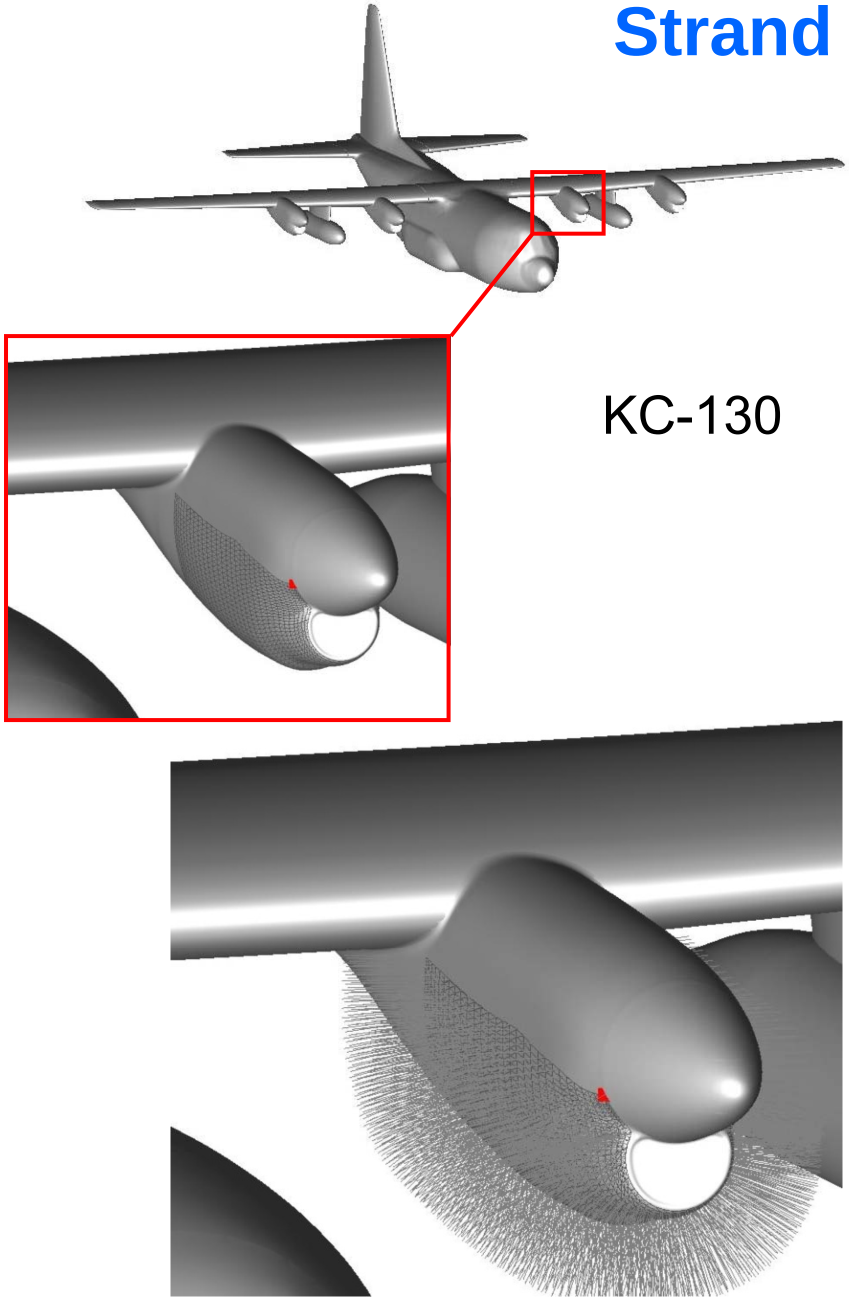




Advantages Available via Strands

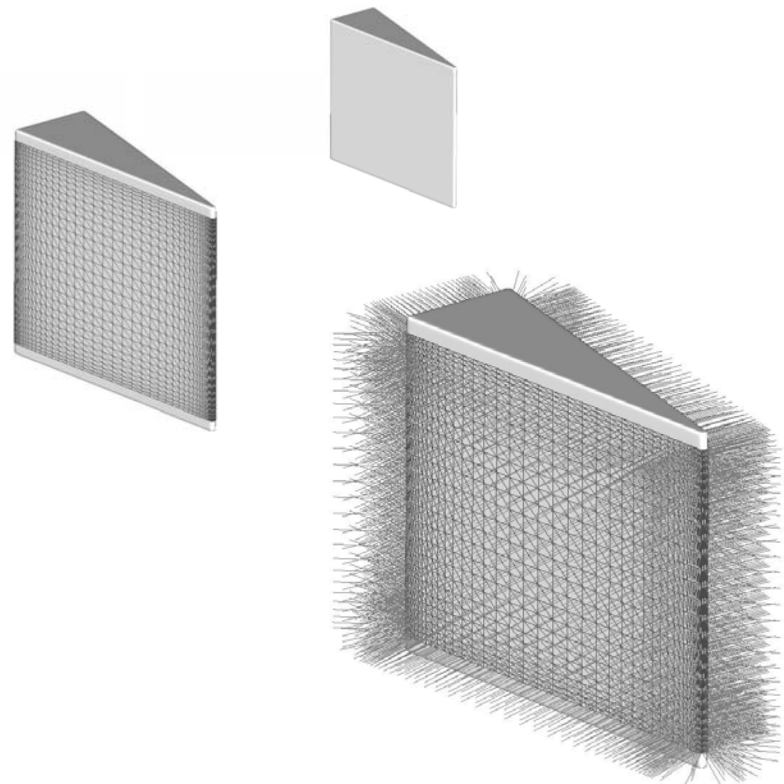
- **Strand Attributes**
  - ✓Viscous boundary layer resolution
  - ✓Fully <u>automatic volume mesh generation</u>
  - ✓Enables fully <u>automatic domain connectivity</u>
  - ✓Enables self satisfying domain connectivity (i.e., parallel efficiency)
  - ✓Enables fully <u>automatic AMR in near-body domain</u>
  - ✓Low memory for VOLUME mesh – need memory only for…
    - Surface vertices and associated connectivity (2D data)
    - Strand Pointing Vector (3 REALS) per surface vertex
    - Strand Clip Point (1 INT) per surface vertex

Strand Examples



KC-130

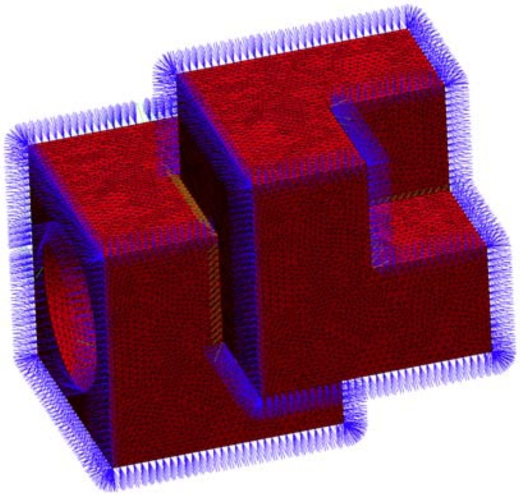
Wedge (insulation foam)

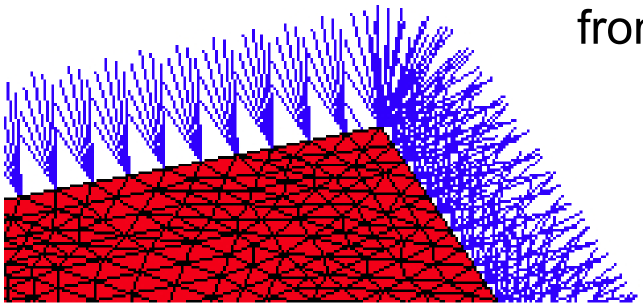


Strand "Oddities" and Treatments

R. Haimes & W. Chan

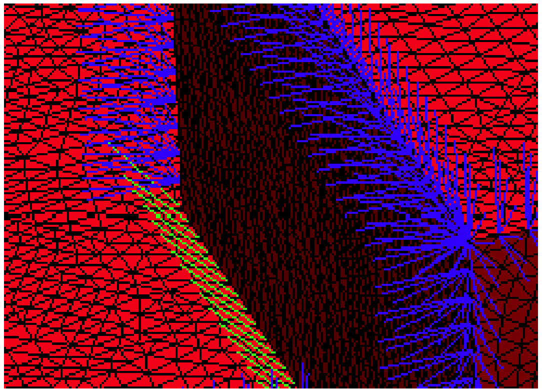
- **Convex Corners**



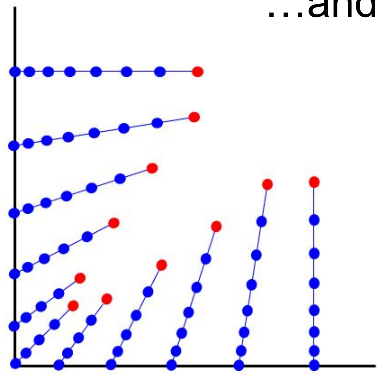


Allow multiple strands to radiate from vertices along convex corners

- **Concave Corners**

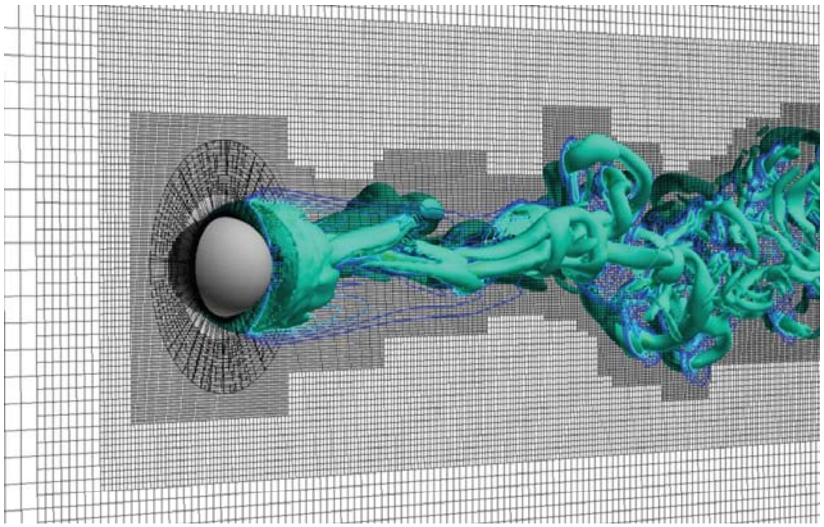


Provide connectivity via off-body telescoping …and (optionally) apply root-bending

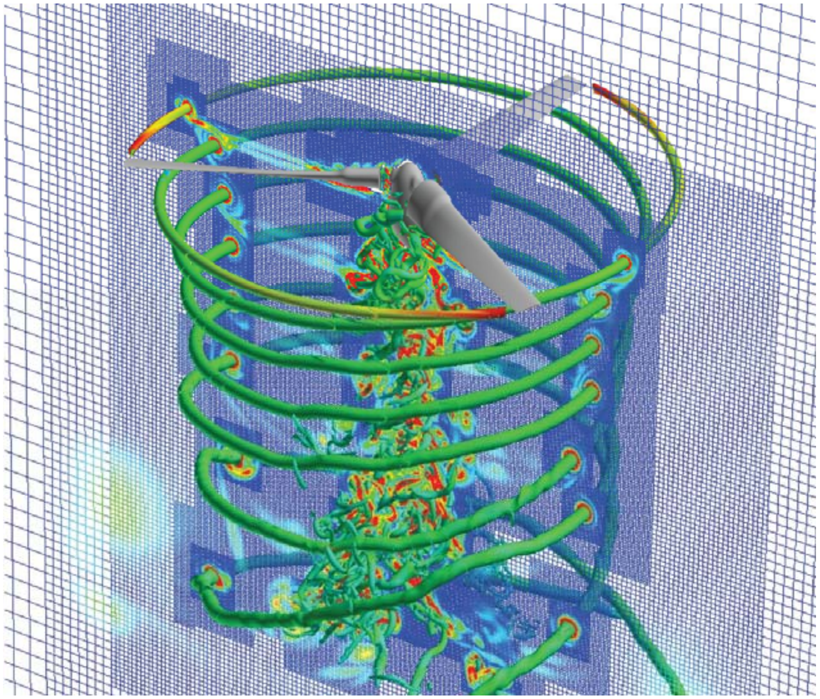


Example Strand-based dual mesh Applications

- **Strand-based dual mesh applications w/ off-body AMR**
  - ✓Flow over a sphere (left) – iso-surface overlaid onto off-body mesh system
  - ✓Isolated TRAM rotor (right) – iso-contour colored by vorticity magnitde



AIAA-2009-3792 (Wissink, et al.)



Summary

- **Realization of envisioned paradigm change requires, of course, that multi-disciplinary, physics-based simulation tools**
  - ✓ Correctly represent the governing physics
  - ✓ Generate data of quantifiable quality

  (i.e., physical accuracy and solution uncertainty quantification are necessary components of the paradigm change enabling technology – this is true for <u>all relevant physics</u> and their interactions)

- **Timeliness issues currently define the critical path**
  - ✓ Surface and volume mesh generation necessary for solution of problem <u>aerodynamics</u> is currently the limiting case
  - ✓ Full automation of surface and volume mesh generation is required for realization of the envisioned paradigm change

Summary (continued…)

- **The Critical Path**
  - ✓Fully Automatic generator for “minimally acceptable” surf mesh (TBD)
  - ✓Fully Automatic Strand mesh generator (Hv5.0)
  - ✓Strand solver (Hv5.0)
  - ✓Fully Automatic near-body Strand AMR capability (TBD)
  - ✓Fully Automatic off-body nested Cartesian mesh generation & mesh manager (Hv3.0)
  - ✓Fully Automatic domain connectivity for Strand-based dual-mesh systems (Hv5.0)

- **Impacts of advances noted above**
  - ✓High fidelity, full-vehicle simulations (including problem setup, simulations, and post process analysis) in **HOURS to DAYS**
  - ✓Simulation tools usable by practicing engineers for…
    - Design verification prior to key decision points
    - Evaluation of planned or potential operational use scenarios
    - Planning/rehearsal of wind-tunnel and full-scale flight tests
    - Performance of flight certifications
    - Calibration of low-fidelity analysis tools associated with conceptual design