National Aeronautics and Space Administration

Flexible Wing Designs with Sensor Control Feedback for Demonstration on the X-56A (MUTT)

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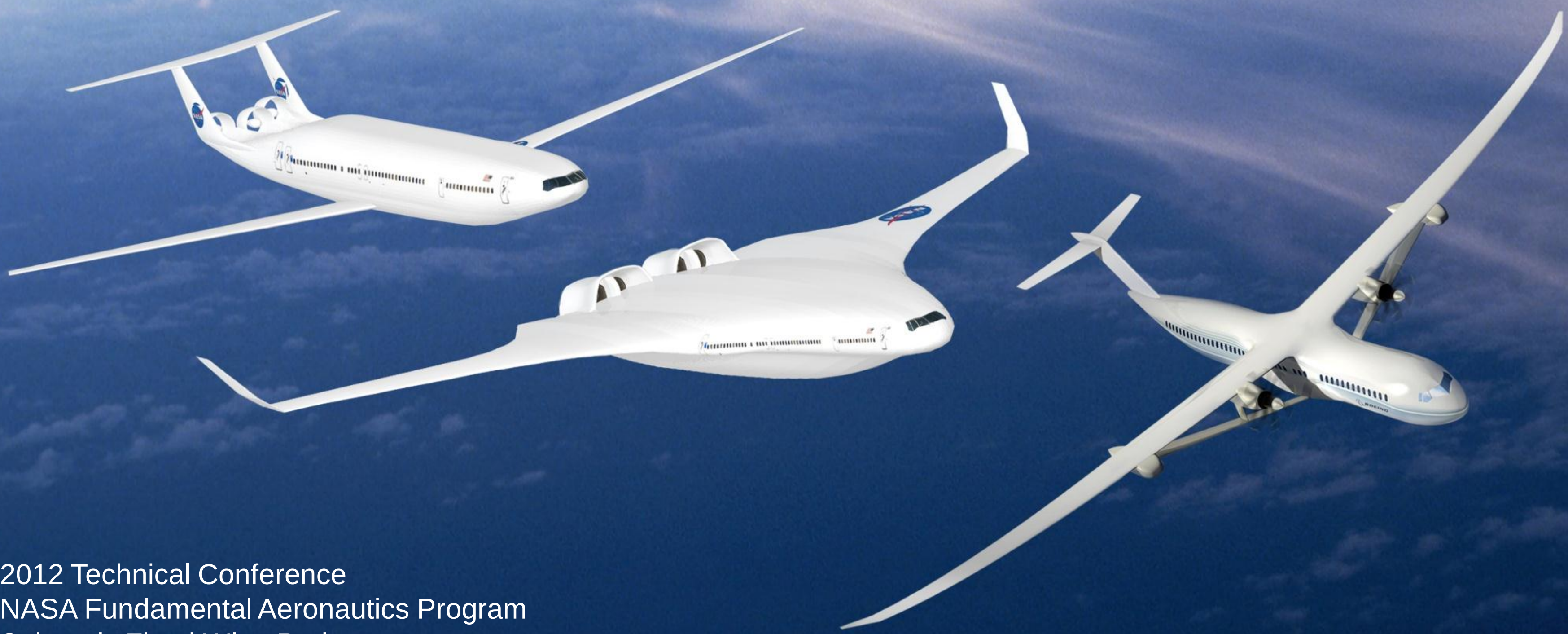

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NASA Fundamental Aeronautics Program
Subsonic Fixed Wing Project
Cleveland, OH, March 13-15, 2012

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Outline

- SFW Strategic Thrusts & Technical Challenges
- High Aspect Ratio Elastic Wing
  - Flight Dynamics & Control **(Chris Reagan)**
  - ASE Controller Design using Distributed Sensing **(Marty Brenner)**
  - Fiber Optic Strain Sensing (FOSS) **(Allen Parker)**
  - Fiber Optic Wing Shape Sensing (FOWSS) **(John Bakalyar/Lance Richards)**
  - Aeroservoelastic Tailored Wings using MDAO **(Chan-Gi Pak)**
  - Passive Aeroelastic Design of High AR Elastic wing **(Jim Moore)**
  - Distributed Control Effectors **(Dan Moerder)**
- Focused System's Research Objectives
  - Access to Models and Flight Data
  - High Aspect Ratio Elastic Wing Technology Roadmap
- X-56a Multi-Utility Technology Testbed (MUTT)
  - **John Bosworth(DFRC Chief Engineer) and Gary Martin (DFRC Project Manager)**

SFW Strategic Thrusts & Technical Challenges

***Energy Efficiency Thrust** (with emphasis on N+3)*
Develop economically practical approaches to improve aircraft efficiency

***Environmental Compatibility Thrust** (with emphasis on N+3)*
Develop economically practical approaches to minimize environmental impact

Energy & Environment

***Cross-Cutting Challenge** (pervasive across generations)*

***TC1 - Reduce aircraft drag** with minimal impact on weight (aerodynamic efficiency)* — *Drag*

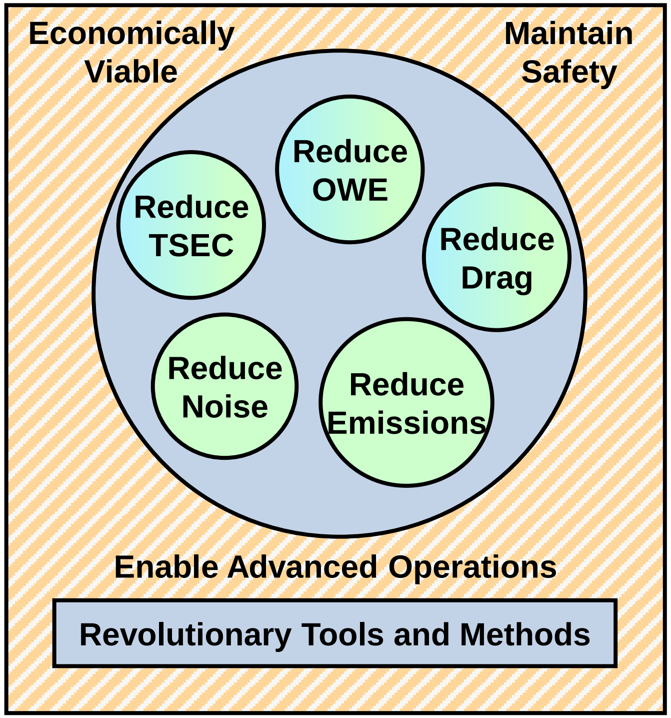
***TC2 - Reduce aircraft operating empty weight** with minimal impact on drag (structural efficiency)* — *Weight*

***TC3 - Reduce thrust-specific energy consumption** while minimizing cross-disciplinary impacts (propulsion efficiency)* — *TSEC*

***TC4 - Reduce harmful emissions** attributable to aircraft energy consumption* — *Clean*

***TC5 - Reduce perceived community noise** attributable to aircraft with minimal impact on weight and performance* — *Noise*

***TC6 - Revolutionary tools and methods** enabling practical design, analysis, optimization, & validation of technology solutions for vehicle system energy efficiency & environmental compatibility* — *Tools*



High Aspect Ratio Elastic Wing
changing the drag/weight trade space

Drag | Weight | TSEC | Clean | Noise

Objective
Explore & develop technologies enabling lightweight high aspect ratio wings

Approach/Challenges

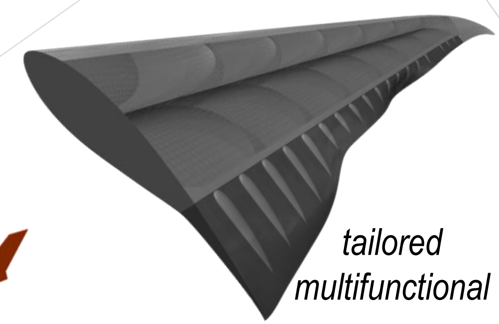
Designer Materials
Aeroelastic Tailoring
Tailored Load Path
Distributed Control Effectors
Aerodynamic Shaping
Elastic Aircraft Flight Control

Benefit/Pay-off
– 25% wing structural weight reduction
– AR increase of 30-40% for cantilever wings, 2X+ for braced

braced

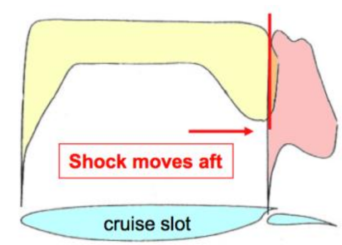
cantilever

active controls load alleviation



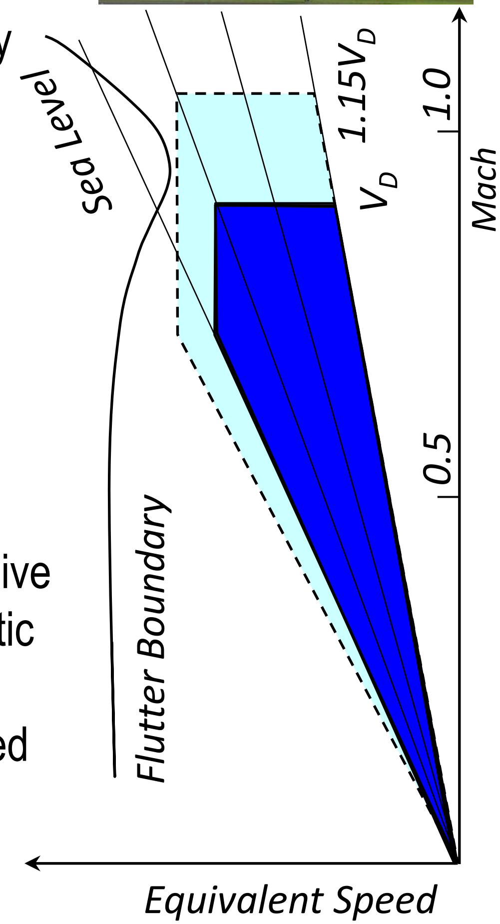
tailored multifunctional

passive/active advanced aerodynamics



Flight Dynamics & Controls

- **History** shows it takes 10-15 years to transition new technology to industry once TRL maturations for Flight Research requirements are met
- **Current Transport Aircraft**
  - Fly-by-Wire (A320-A380, 777,787,747-8 Freighter)
  - Aeroelastic flight controls - A380 Wingspan 261ft, AR~7.5, 747-8 Wingspan 224ft, AR~7
- **High Aspect Ratio Elastic Wing Challenges**
  - Design only for Strength, Panel buckling, Durability and Damage tolerance within the Vd envelope
  - No additional stiffness (extra margins) for Surface effectiveness, Passive Control (aeroelastic wing tailoring) of dynamic response and aeroelastic instabilities (use active suppression)
  - Need to demonstrate reliability (robustness) equivalent to that achieved by stiffer structure.
  - Improvements needed in: Modeling, Sensors, Actuation, Control Algorithms



AeroServoElastic Controller Design using Distributed Sensing

- AAW represents a new philosophy for reducing structural weight and improving aerodynamic efficiency and control effectiveness.

- AAW demonstrated equivalent banking or rolling performance
  - Using wing aeroelastic effects alone
  - Smaller control surface movements
  - No differential stabilator

Leading Edge Stagnation Point (LESP) Tao Sensor Verification on ATW-II

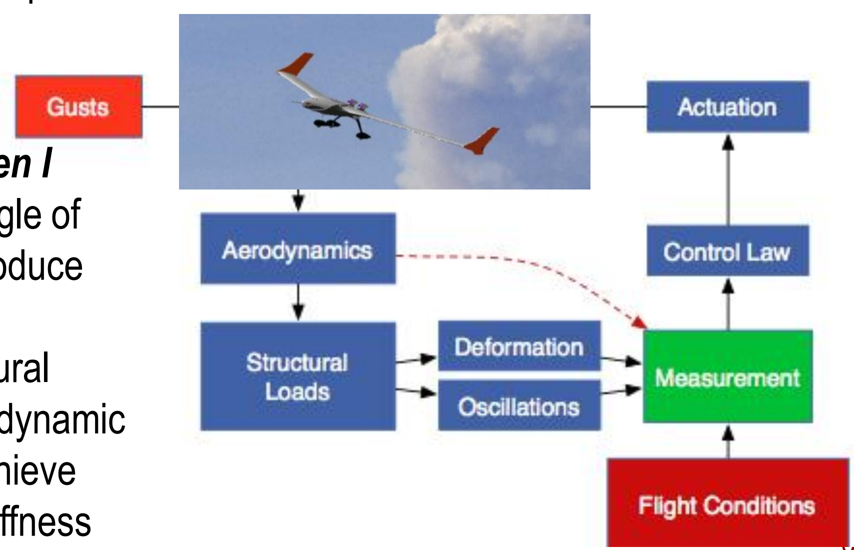
- Characterized flow over ATW-II in flight conditions that a wind tunnel is unable to perform.
- LESP was able to track leading edge separation right before flutter
- LESP was able to keep track lift after stall

X-56a ASE Controller Gen I

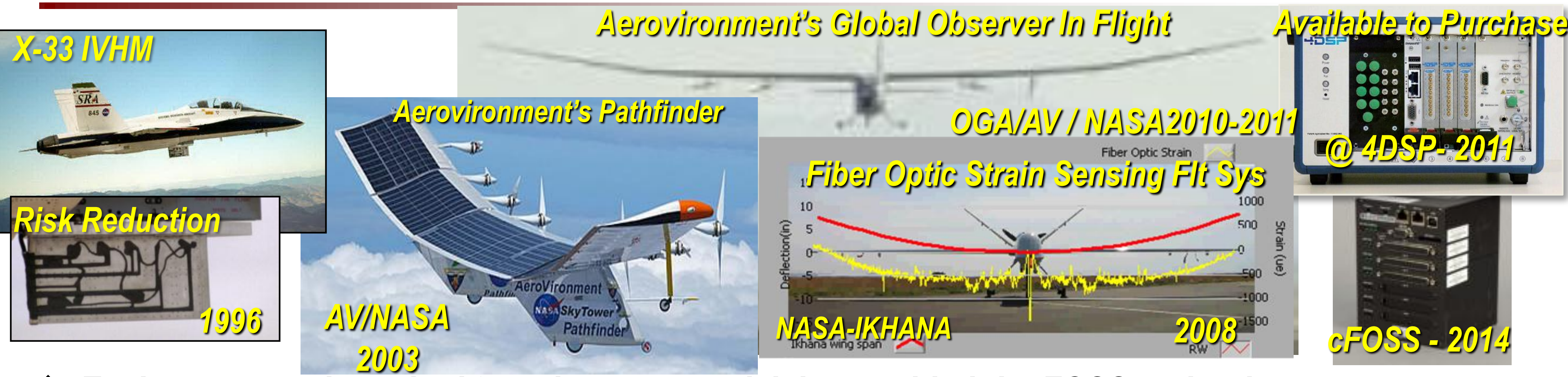
- Use pitch rate and angle of attack feedback to produce apparent stability
- Use distributed structural deformation and aerodynamic flow information to achieve apparent structural stiffness

X-56a ASE Controller Design using Distributed Sensing Gen II

- Hybrid Controller using models and sensor only information to control the structure
- LESP sensors to operate near performance stability limits and rely on models as little as possible



Fiber Optic Strain Sensing (FOSS)



- ***Each program above had 'requirement needs' that enabled the FOSS technology to mature***
- ***Taking new technology to flight, bounds the research path, creates innovation and pushes the invention of more technologies***

Ground Sys TRL 1-2					Flt TRL 2		Grd TRL 3-4			Flt TRL 3		Grd TRL 5		Flt TRL 4		Flt TRL 5-6		
FY96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14

1996 flew Contractor fiber optic instrumented flight test fixture with limited success. Laser not flight worthy. Capable of only one sample/second.

2001 Ground Based System

20 Ft Fiber, 480 Sensors, 1/3 Hz

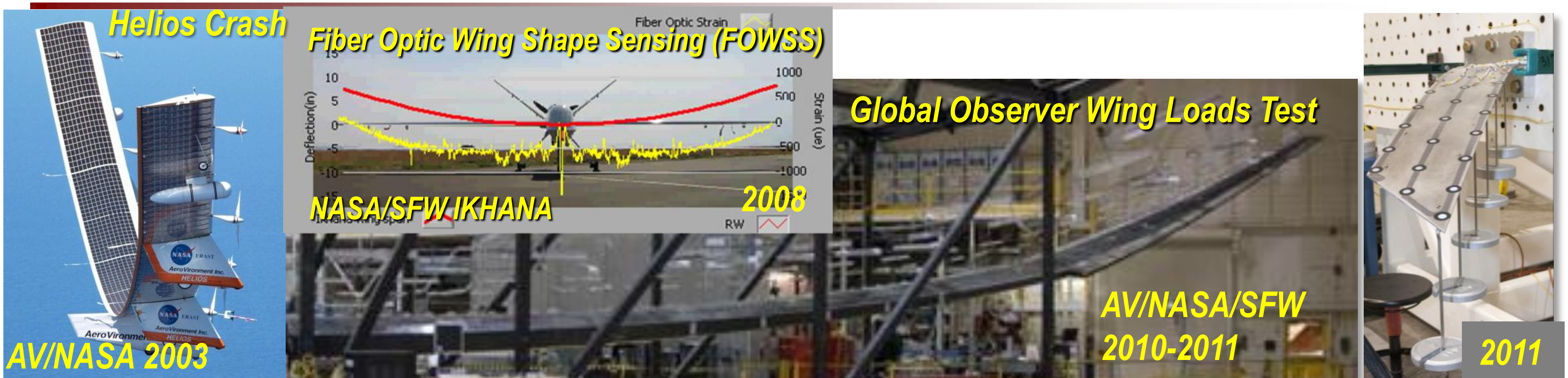
2003 Small Flight System prepared for Pathfinder Flt

2004 Grd/Flt Sys prep for Ikhana demo. Patent Pending for DFRC Real-Time Processing Capability. Integrated flyable laser.
2008 FOSS proved flight worthy on IKHANA w/ real-time Telemetered data to the ground
4 Fibers, 2000 sensors, 30 Hz, 20lbs

2010 Grd/Flt Sys prep for Global Observer demo. Polarization mitigation. 50/50 broad-band reflector and FPGAs
2011 NASA-DFRC Ground System licensed to 4DSP for purchase
2010-2011 FOSS was used for primary data in post processing
8 Fibers, 8000 sensors, 60 Hz, 30lbs

2011 Compact Flt Sys development for X-56a demonstration. cFOSS will demonstrate: Optics-on-a-Chip, FPGA Mezzanine Card (FMC) and a new standard for stackable FMC.
2014 cFOSS flight demo on X-56a
16 Fibers, 32000 sensors, 100 Hz, 10lbs

Fiber Optic Wing Shape Sensing (FOWSS)

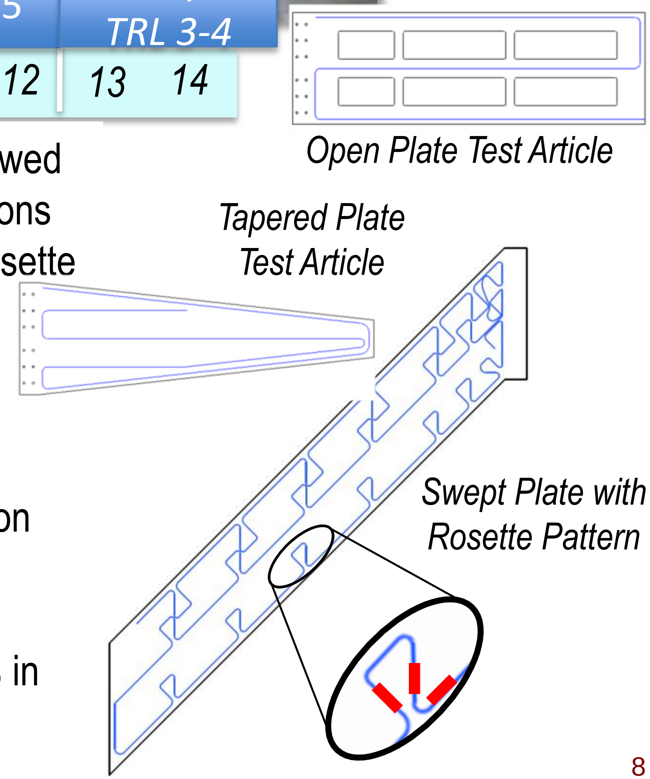


Ground Sys TRL 2-3				Flt Sys TRL 2-3		Grd Sys TRL 4-5				Flt Sys TRL 3-4	
03	04	05	06	07	08	09	10	11	12	13	14

2003 Helios crash attracted interest In control of wing dihedral.
2006 Patent Pending for real-time shape measurement
2007 Performed IKHANA loads calibration using FOSS with photogrammetry validation of shape.

2008 Validated the Flight System Capability of measuring shape real-time in flight
2010 Global Observer Wing Loads Test performed w/ Photogrammetry proved bending predictions <1.0% error

2011 Fiber layout research showed no effected on bending predictions for various wing planforms . Rosette fiber layout proved to be more versatile for torsion shape predictions of complex structures
2012 EQDE prediction for torsion showing promise within 0.25 degrees, an RMS error of 0.08 degrees. This means within 5% in most cases.



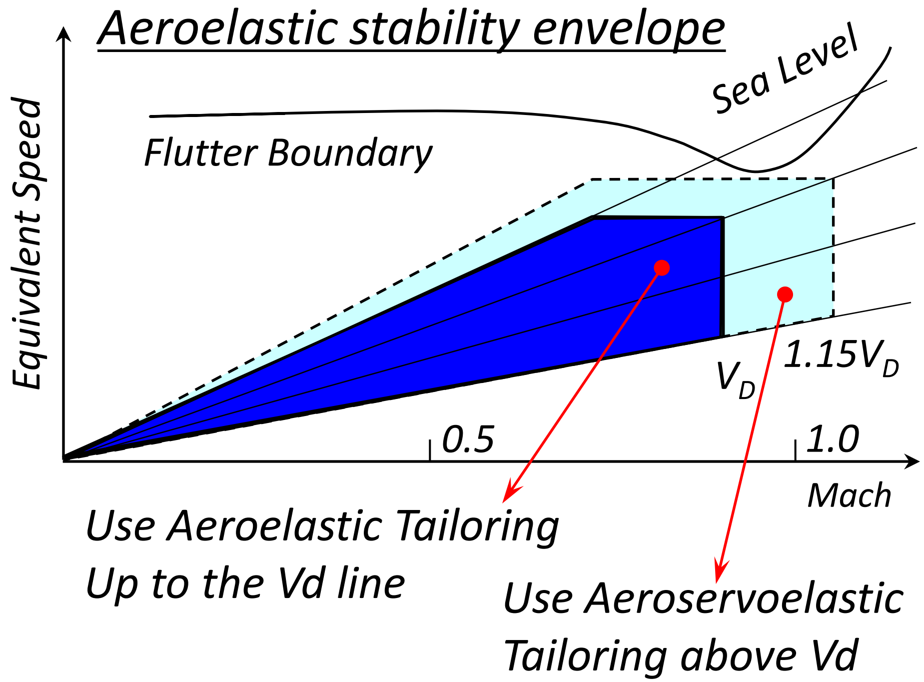
Aeroservoelastically Tailored Wings using MDAO

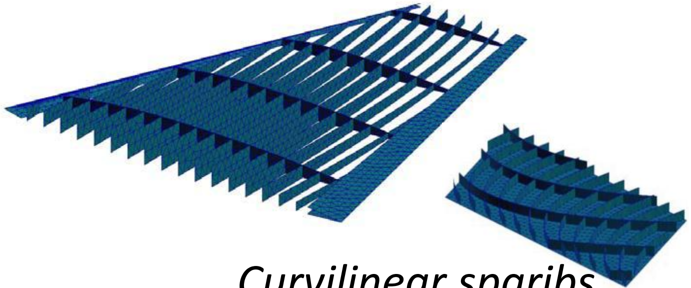
Research Goals/Objectives

- ❑ Use aeroelastic tailoring theory and active flexible motion control technique to satisfy the overall strain, aeroelastic and aeroservoelastic instability requirements within given flight envelopes
- ❑ Use curvilinear sparib concept as well as composite ply angles for aeroelastic tailoring

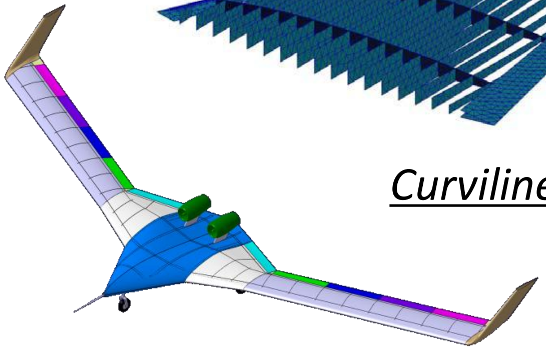
Approach

- ❑ Simultaneously update structural as well as control design variables during early design phase
- ❑ Design AR10 Wing using object-oriented MDAO tool
  - ❖ Design scaled AR10 wing using structural model tuning tool
- ❑ Design AR14 Wing using Object-Oriented MDAO tool
  - ❖ Design scaled AR14 wing using structural model tuning tool





Curvilinear sparibs



X-56A

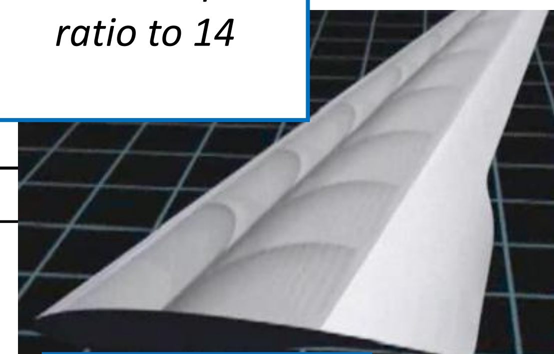
Passive Aeroelastic Tailored High Aspect Ratio Wings

BACKGROUND

State-of-the-art assessment - aeroelastic tailoring → *ID tailoring approaches* → *ID optimization strategy & constraints*

DESIGN

Baseline FEM
Start w/aspect ratio=10
→ *Static structural & AE analysis* → *Design of experiments – structural AE tailoring sensitivity analysis* → *Optimization*
NEXT STEP = increase aspect ratio to 14



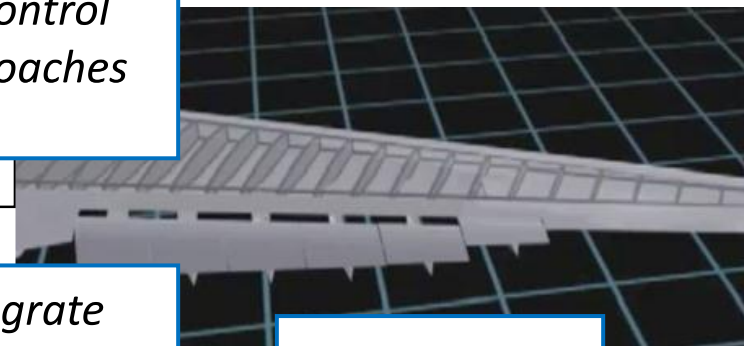
TEST

Full scale design → *Structural panel testing w/integrated fiber optics* → *Dynamic scaled X-56A test*
w/fiber optic shape sensing → *Add novel control effectors*

Distributed Control Effectors

TRADE STUDY

Trade off drag, weight & noise to ID optimal control effectors → ID control approaches



HARDWARE

ID requirements: actuators, flexible skin material, optimal number of control effectors → Functional bench test → Integrate distributed control effectors onto stiff & flexible wings → Flight testing on X-56A for flight control effectiveness

CONTROLS

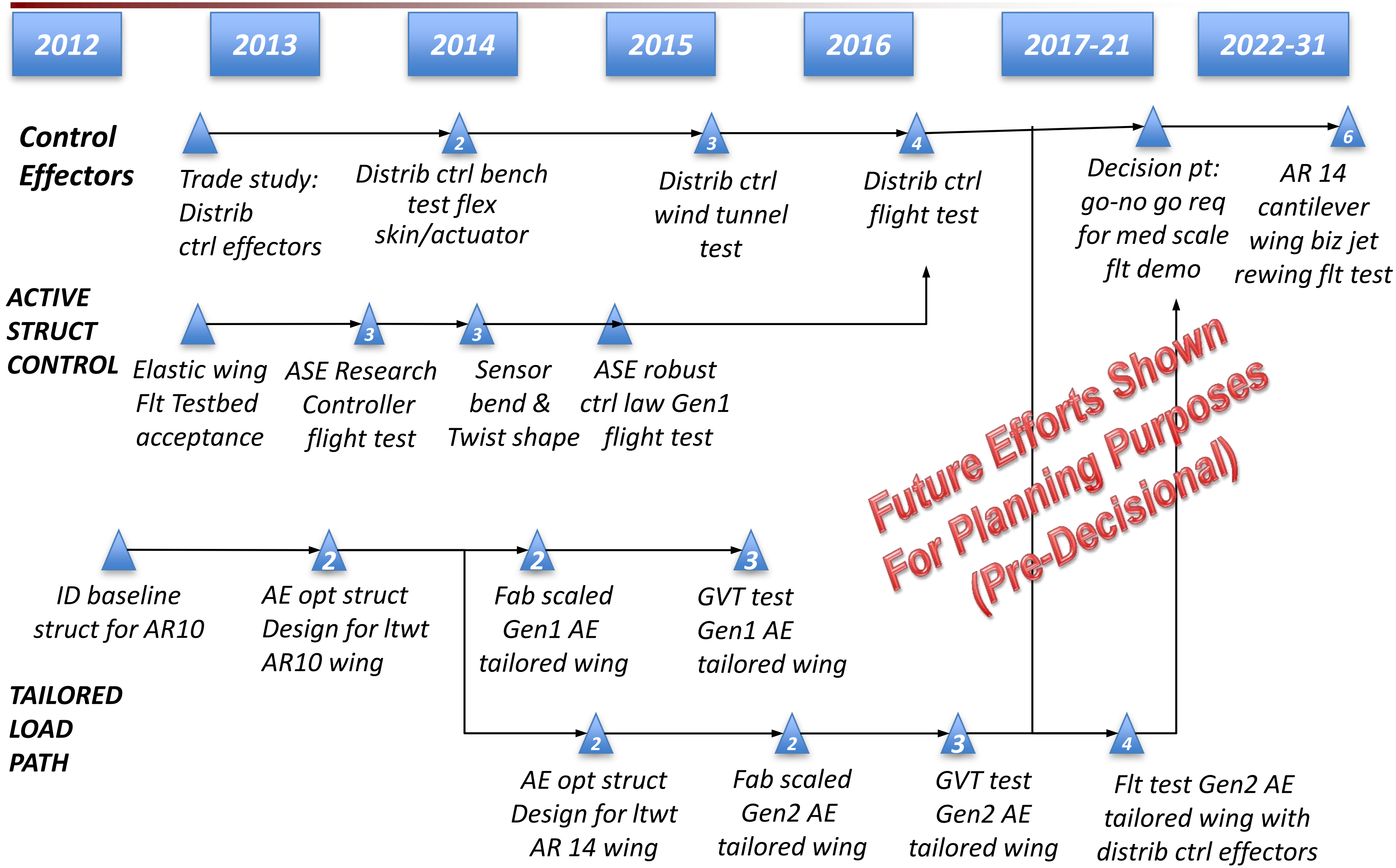
Flight control laws for distributed control effectors → Add aeroservoelastic controls → Control allocation to min. wing loading → Wing shape control for drag reduction

Focused *System's* Research Objectives

1. **Provide *non-proprietary* NASA designed flight control system for X-56A vehicle – emphasize *open source* publication**
2. **Develop robustness criteria for actively controlled flexible vehicles**
3. **Integrate emerging sensor technology such as FOSS and LESP as feedback to the flight control system**
4. **Demonstrate compact FOSS system in flight environment**

   - In work: Compact FO System, Fiber-Based Ring Laser, Optics on a Chip, Ruggedizing Fiber, Twist Shape Prediction, Adaptive Spatial Density Algorithm using Continuous Grading Fiber, 3-core fiber manufacturing
5. **Use FOSS and LESP flight measurements to validate and improve the MDAO analysis and prediction capability**
6. **Demonstrate ability to derive onboard in real time, shape and load information from the FOSS system**
7. **Using MDAO, design, fabricate, and flight demonstrate an integrated dynamically scaled wing structure with distributed sensor and control effectors**

High Aspect Ratio Elastic Wing Roadmap

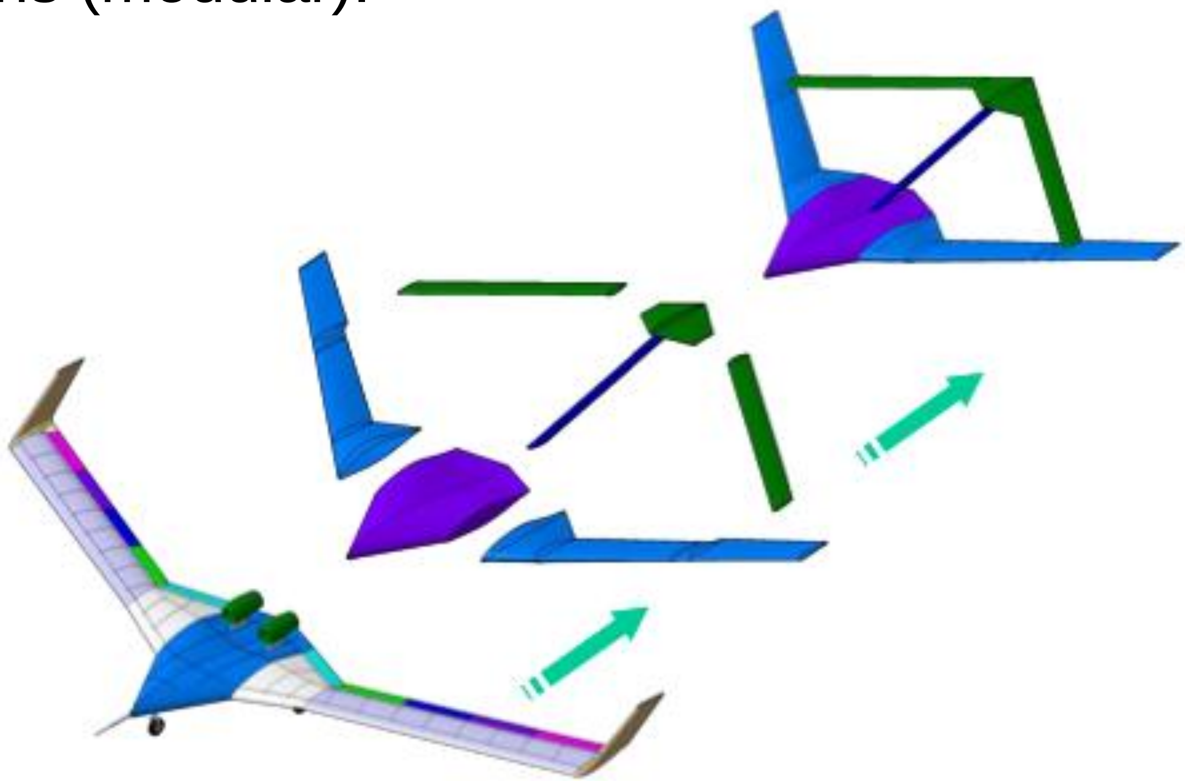


Multi-Utility Aeroelastic Demonstration (MAD) Objectives

- Develop a Multi Utility Technology Test-bed (MUTT) vehicle that can be utilized in flight research of active aeroelastic control technologies and Gust Load Alleviation.
- The approach here would be to reduce scale (and cost) and use the vehicle to validate tools and concepts that could be applied to larger future vehicles.
- For example, Boeing's 747-8 has a wing span of 224ft, but the MUTT is only 28 ft. While it is not truly aeroelastically scaled, *it does* exhibit the aeroelastic phenomena of the larger highly flexible future transport vehicle and is useful for validating design and analysis methods that could then be applied to future transports.
- The MUTT vehicle will be capable of performing High Risk Flight Demonstrations using a certified drogue shoot recovery system.
- On Jan 2012 MUTT was given the designation of X-56A

MUTT Alternative Planform Accommodation

The MUTT vehicle will be capable of a variety of configurations (modular).

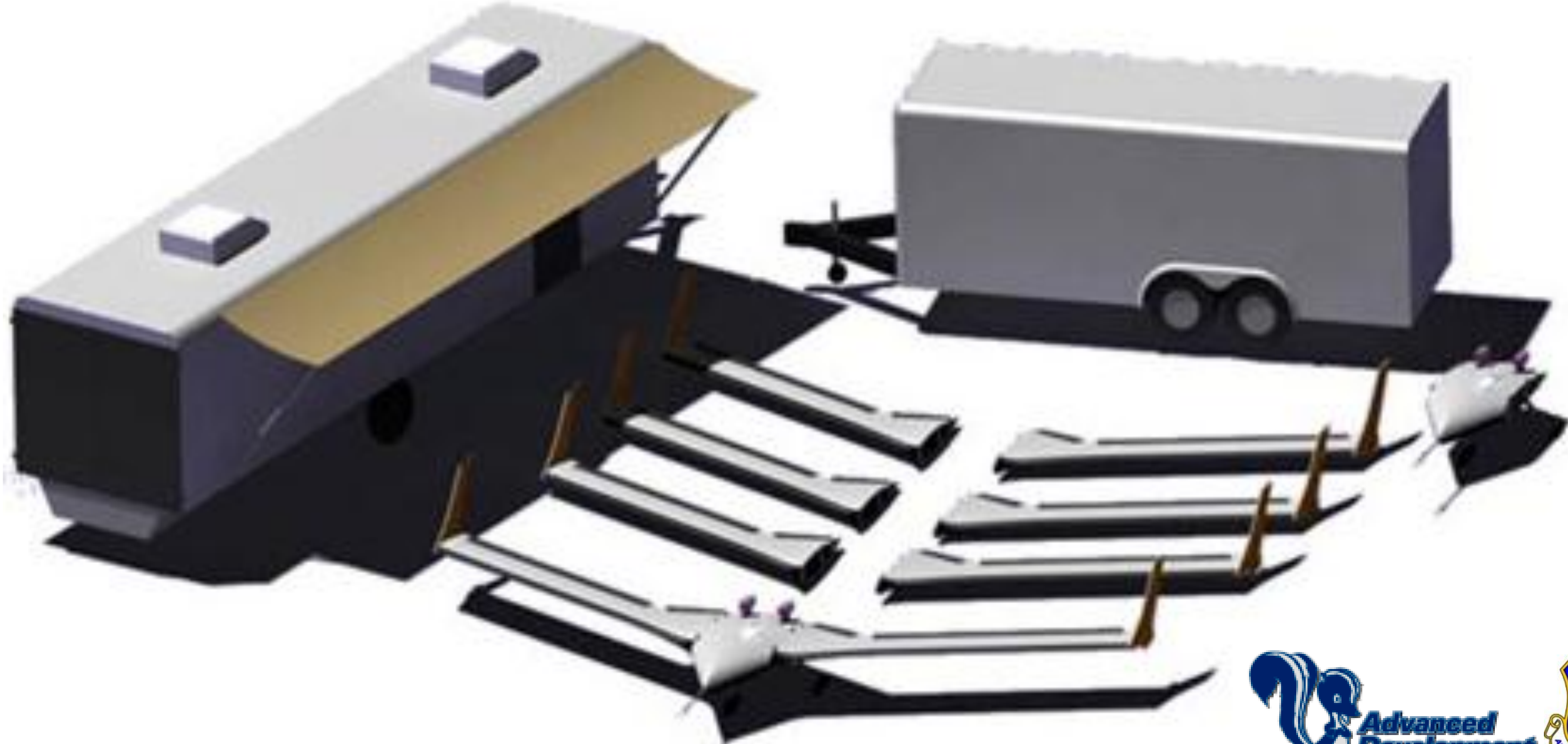


X-56A

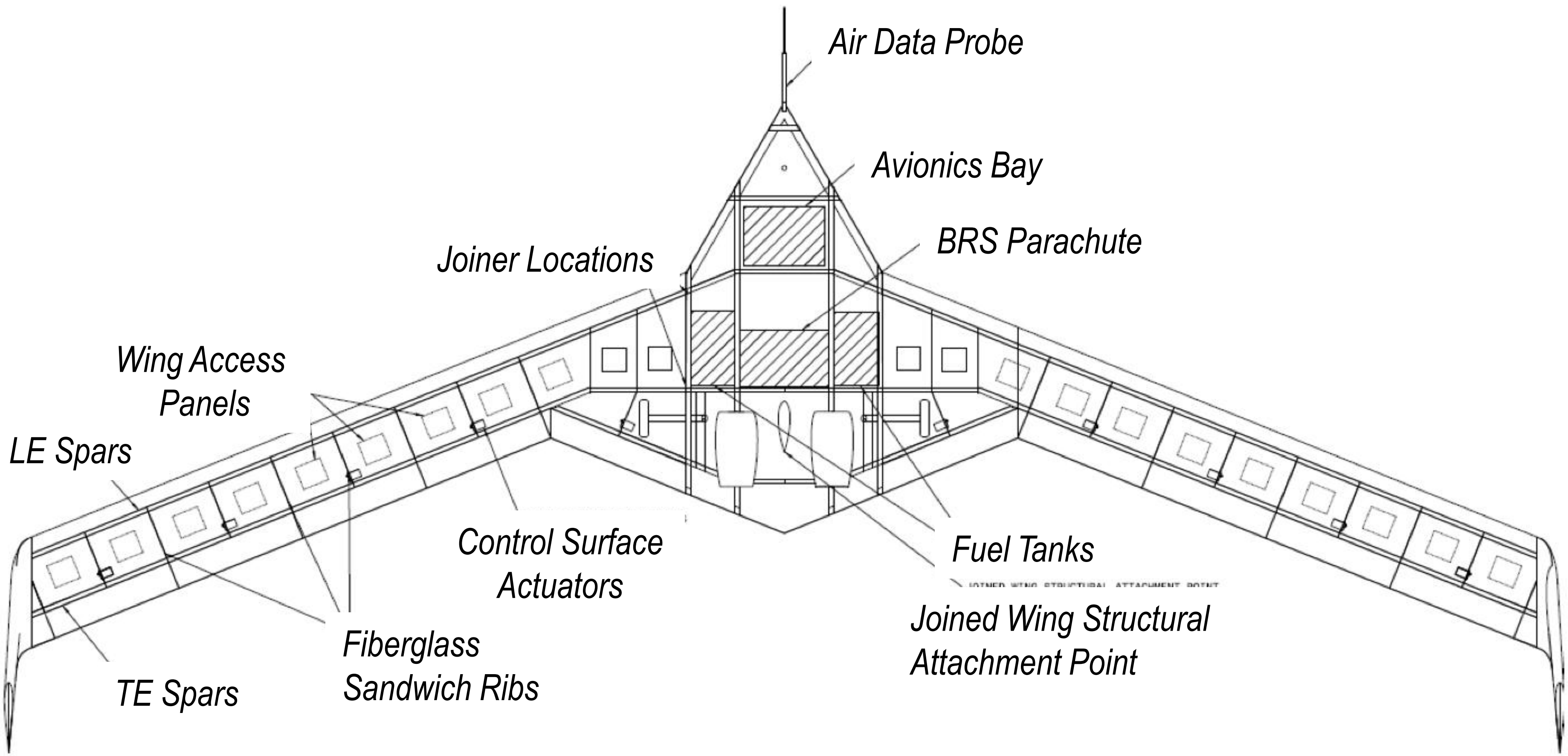
X-56A Deliverables from AFRL / LMCO

Complete Research System

- 2 Center Bodies
- 1 Stiff Wing Set
- 3 Flexible Wing Sets
- 1 Ground Control Station
  - With Simulation and SIL Capabilities



X-56A General Arrangement



X-56A

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Conceptual Design of a Multi-utility Aeroelastic Demonstrator

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