Multi-Scale Structural Mechanics and Prognosis

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Integrity ★ Service ★ Excellence

Report Documentation Page

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NAME: David Stargel

BRIEF DESCRIPTION OF PORTFOLIO:

FLIGHT STRUCTURES: Fundamental basic research into structural mechanics problems relevant to the US Air Force

Structural mechanics or **Mechanics of structures** is the computation of deformations, deflections, and internal forces or stresses (*stress equivalents*) within structures, either for design or for performance evaluation of existing structures*

LIST SUB-AREAS IN PORTFOLIO:

Novel flight structures
Multi-scale modeling and prognosis
Structural dynamics

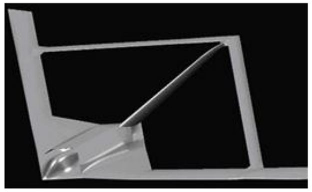
Focus w/in sub-areas

Computing
Predicting
Enabling

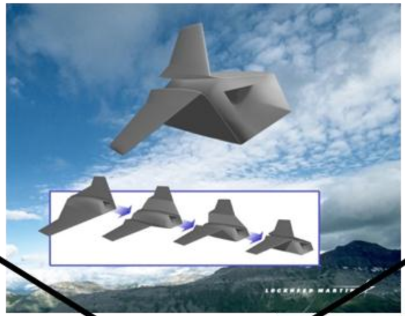
*** From Wikipedia**

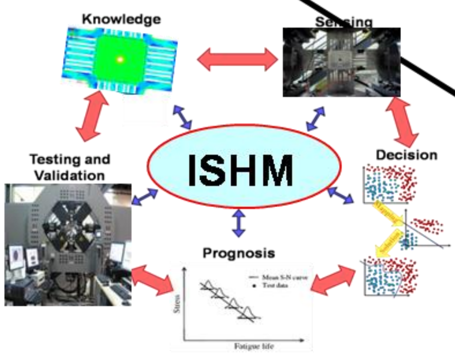
Thrust Areas

Novel Flight Structures



- Morphing Aircraft
- Flapping Wing Air Vehicles
- Non-traditional Structural Configurations

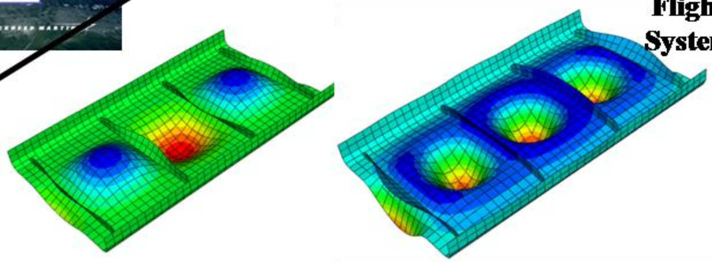




- Structural Health Monitoring
- Non-destructive Evaluation
- Prognostics
- Physics-based Modeling

Multi-scale Modeling and Prognosis

Untested Flight System



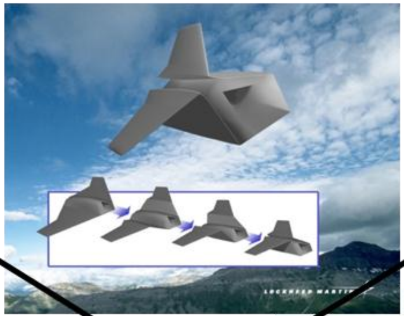
- Thermo-acoustic Response
- Space Structures

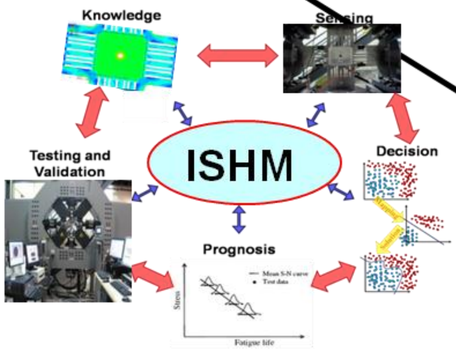
Structural Dynamics

Challenges

Novel Flight Structures

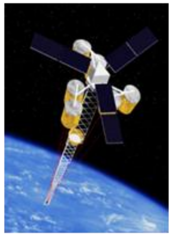
- Multi-disciplinary Design Problems
- Non-traditional Structural Configurations
- Student Education

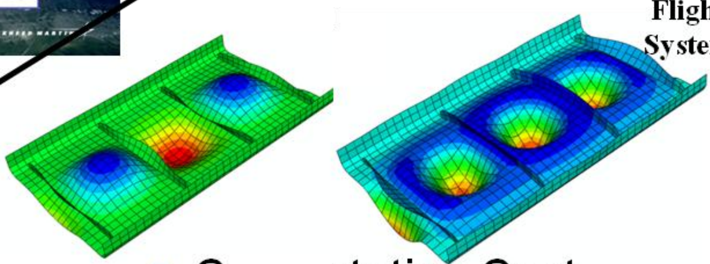




- Uncertainty/Variability
- Probability of Detection
- Verification & Validation
- Time & Length Scale Couplings

Multi-scale Modeling and Prognosis

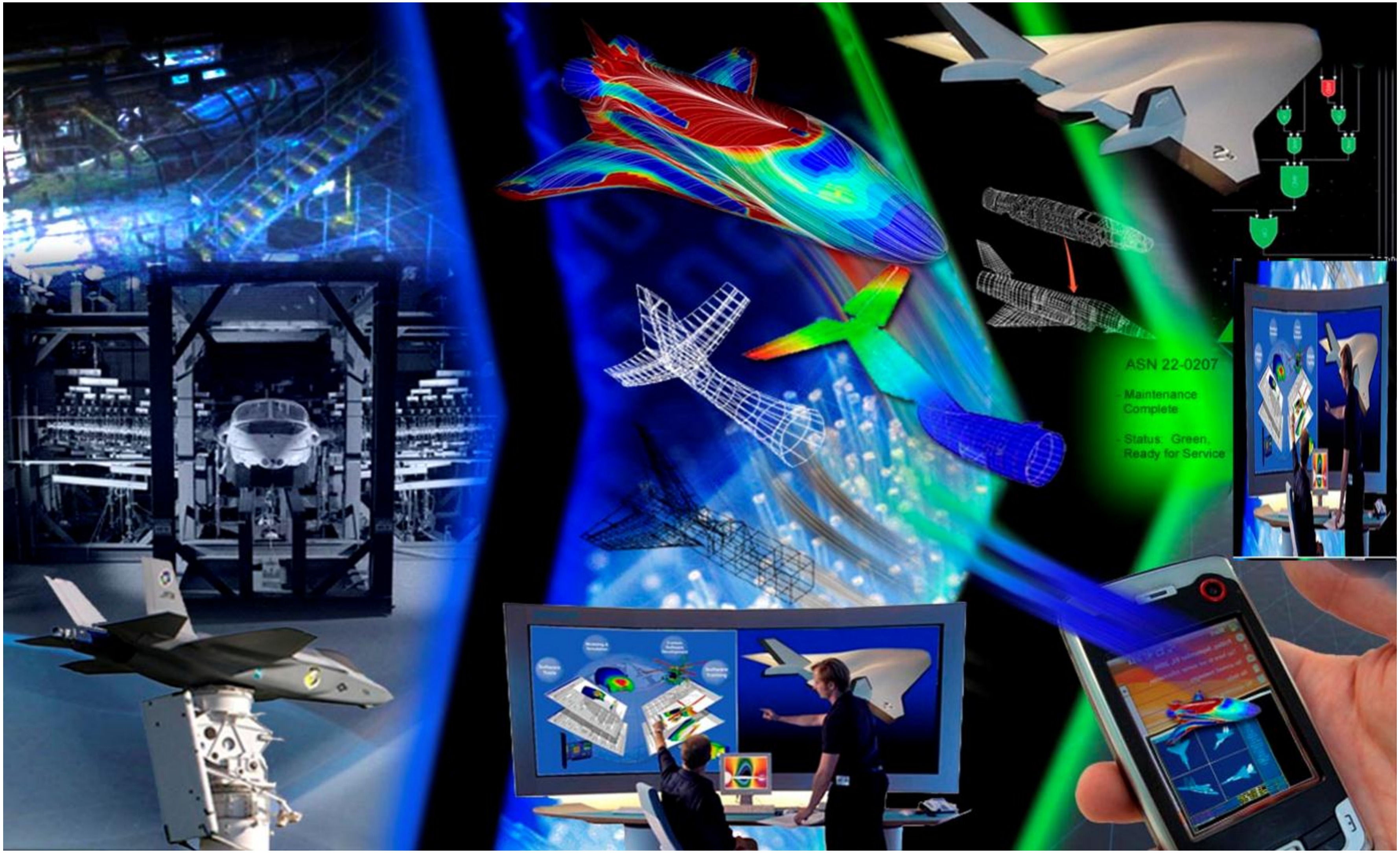




- Computation Cost
- Non-linear Interactions
- Testing Environments

Structural Dynamics

Structural Mechanics Vision of Future Weapon Systems



AFRL

Exploratory & Anticipated Research

"**The first essential of the airpower necessary for our national security is preeminence in research…**"
Gen. Henry "Hap" Arnold, 1944

"There was a view that we had advanced to a stage of aircraft design where we could design an airplane that would be near perfect the first time it flew. … I think we've demonstrated in a compelling way that that's foolishness."
Gen. Norton Schwartz, USAF Chief of Staff From Defense News, 3/12/12

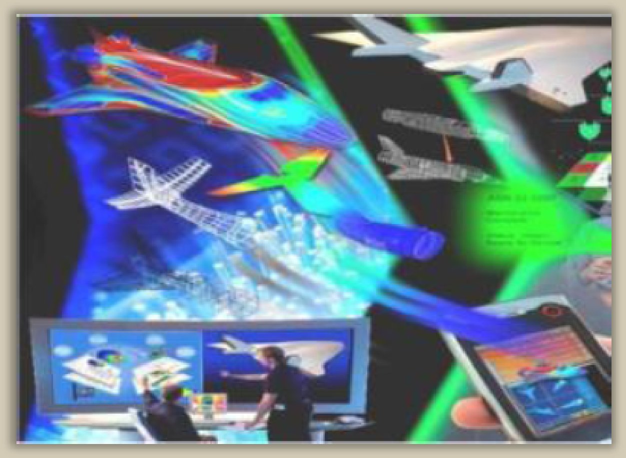
Seldom occurs as a result of addressing today's problems

New solutions to the direct projection of today's problems

Digital Twin Vision

"Digital Twin": Real-Time, High-Fidelity Operational Decisions for Individual Aircraft Enabled by Tail Number Health Awareness

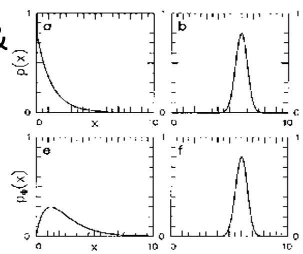
- When physical aircraft is delivered, a Digital Model of the aircraft – specific to that tail number, including deviations from the nominal design – will be delivered as well.
- The Digital Model will be flown virtually through the same flight profiles as recorded for the actual aircraft by its on-board SHM system.
- The modeling results will be compared to sensor readings recorded by the SHM system at critical locations to update / calibrate / validate the model.



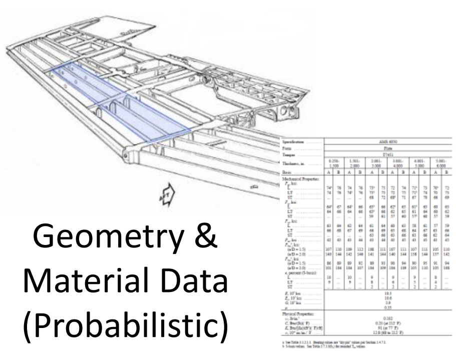
- As unanticipated damage is found, it will be added to the Digital Model so that the model continually reflects the current state of the actual aircraft.
- Prognostics for the airframe will be developed by "flying" the Digital Model through possible future missions.
- The Digital Model will be used to determine when & where structural damage is likely to occur, and when to perform maintenance.

Anticipated Digital Twin Research

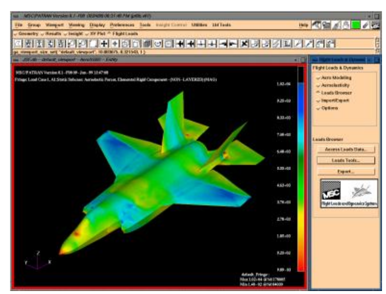
Decision: Fly or Fix



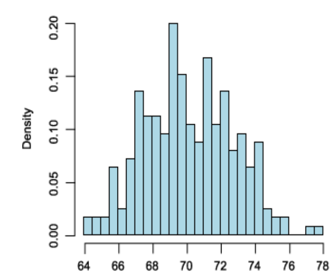
Applied Loads & Environments (Probabilistic)



Geometry & Material Data (Probabilistic)



Physics-based Multi-scale, Multi-Discipline Models



Range of Structural Response & Reliability (Probabilistic)

Quantification of Model Form Uncertainty in Physics-Based Simulations

Christopher Corey Fischer (WSU)

MSTC-CCMS TAC Review

14-15 November 2012

Uncertainty in ESAV Design

Representative ESAV N^2 Diagram

Propulsion	Flow behind inlet shocks	Flow-through panels' data	Temp., Press., Alt., M, Dimen.	Engine weight	Engine weight	Engine data in flight envelope	Thrust available for vectoring		Exhaust speed and temp.		Thrust, Altitude, Mach #, BPR, etc.
Cowl and Inlet	**Geometry**	Configuration, Mach #, Alt.	Cowl, Aft deck	Configuration	Tank and engine	Wing area	Control effector data	Configuration	Noise shielding factor	Configuration, Fuel volume	Configuration
		Aerodynamics	Skin temp., Loading	Aerodynamic Loading		Aero. data in flight envelope	Stability derivatives				
			EEWS	EEWS weight	Structural weight - EEWS						
				Structures	Structural weight - other					Structural failure	
					Weights	Aircraft weight in flight envel.	Inertial properties				Take-off gross weight
						Mission Performance				Fuel volume, Req. maneuvers	Feasibility
							Stability and Control			Added removed fuel volume	Feasibility
								RADAR Cross Section		RCS metric	
									Noise	Noise output	
										Constraints	Feasibility
Thrust, Altitude, Mach #, BPR, etc.	Configuration										**Optimization**

Types of Uncertainty

Mathematical Model to Predict System Response

$$Y = g(X) + \varepsilon$$

Model Form Uncertainty

Present in having different models that represent the same system response, but not positive as to which one of these models is most accurate

- Adjustment Factor Approach
- Bayesian Model Averaging
- Probabilistic Adjustment Factors Approach

Parametric Uncertainty

Inherent in input parameters within a model

- ***Natural variability*** in input parameters
- ***Inconsistency*** in manufacturing processes
- ***Imprecise*** statistical data

- Evidence Theory
- Probabilistic Analysis
- Sampling Approaches

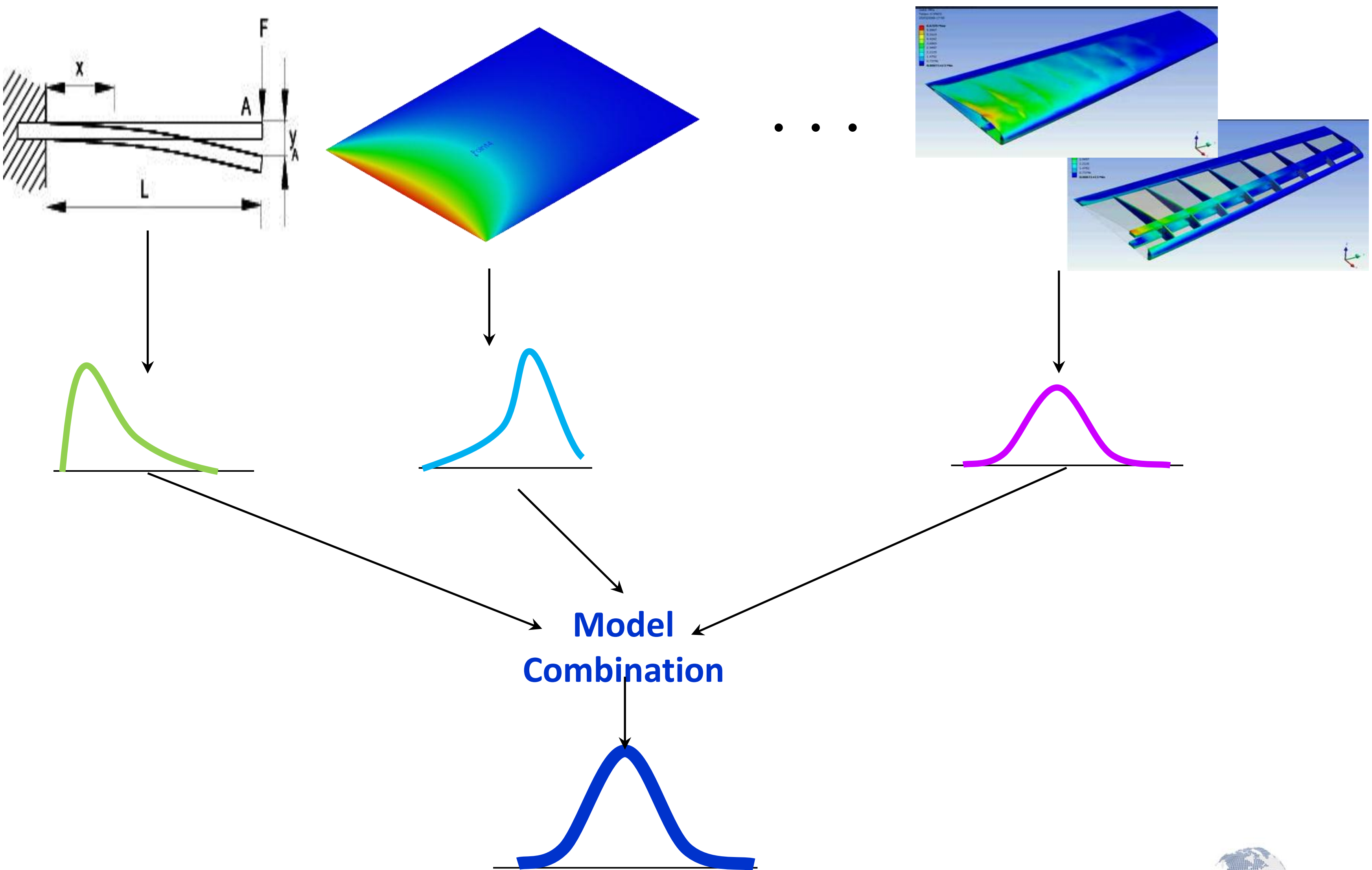
Predictive Uncertainty

Indicates variations in errors of a model's predictions

- ***Differences*** exist between observed experimental data and model predictions

- Bayesian Approach
- Regression Analysis

Combination of Model-Form and Other Uncertainties



Bayes’ Theorem

- **Bayes’ theorem can be used to update prior model probability into posterior model probability given experimental data**

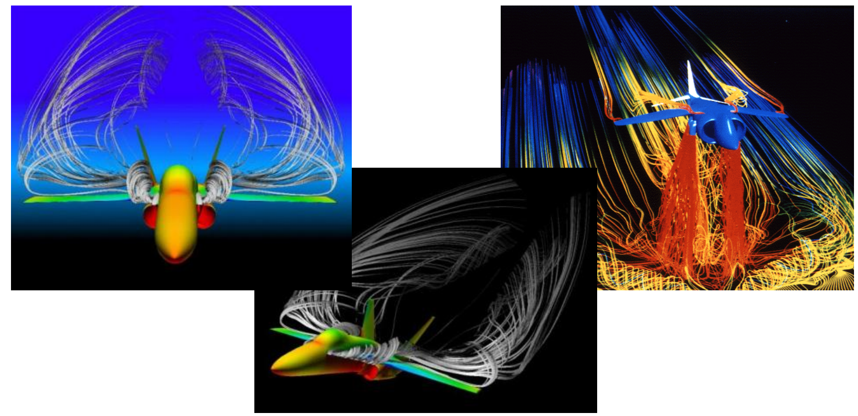
Bayes’ Theorem

$$P\left(M_j \middle| D\right) = \frac{P\left(M_j\right) P\left(\mathrm{D} \middle| M_j\right)}{\sum_{i=1}^{K} P\left(M_i\right) P\left(\mathrm{D} \middle| M_i\right)}$$

Model Likelihood

$$L\left(M_j \middle| \mathrm{D}\right) = P\left(\mathrm{D} \middle| M_j\right) = \left(\frac{1}{2\pi(\hat{\sigma})^2_{mle}}\right)^{N/2} e^{-N/2}$$

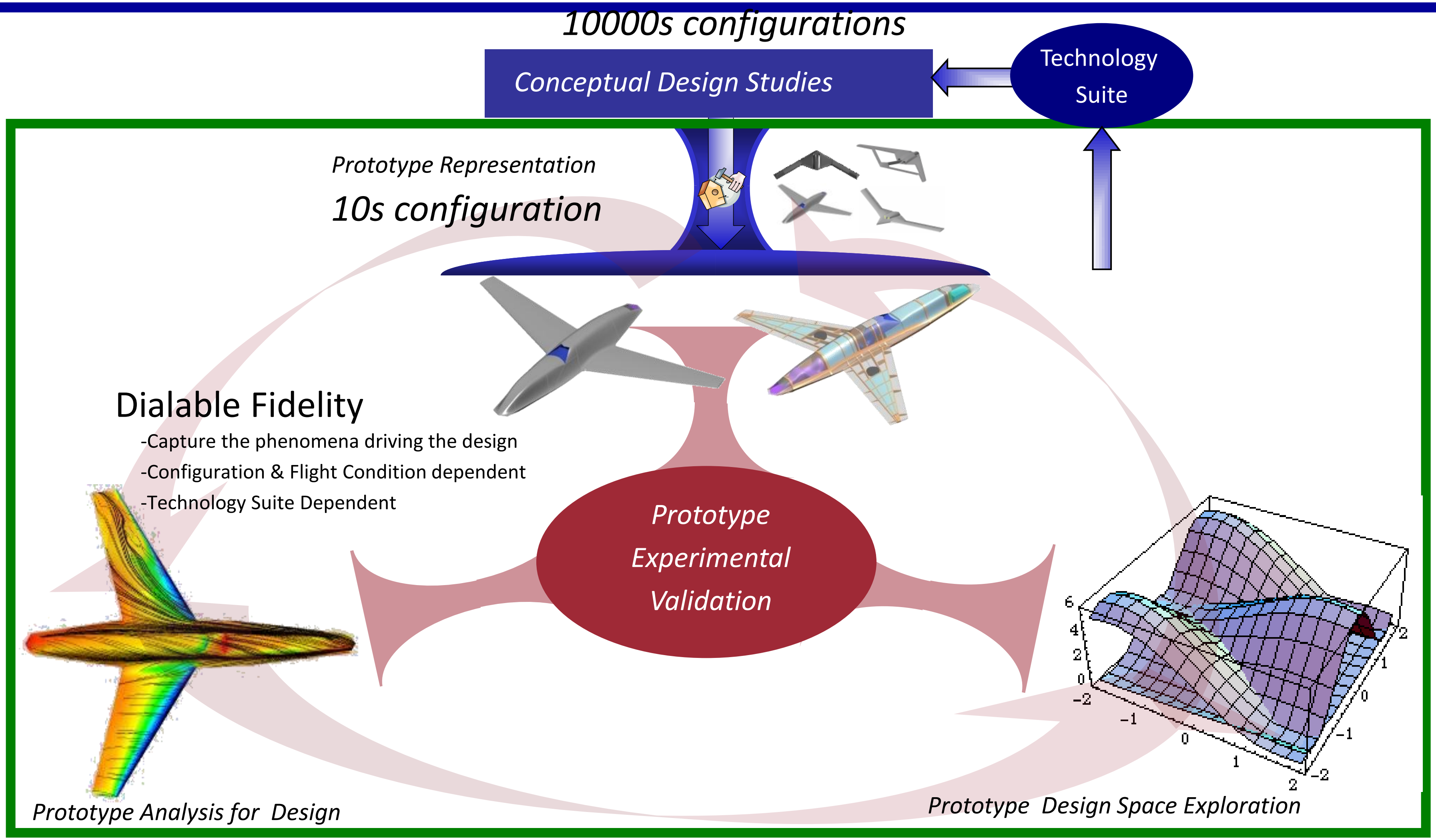
$$\text{where } \left(\hat{\sigma}_j\right)_{mle} = \sqrt{\frac{\sum_{i=1}^{N} \varepsilon_{j_i}^2}{N}}$$



Models 1 - K

Experimental Data

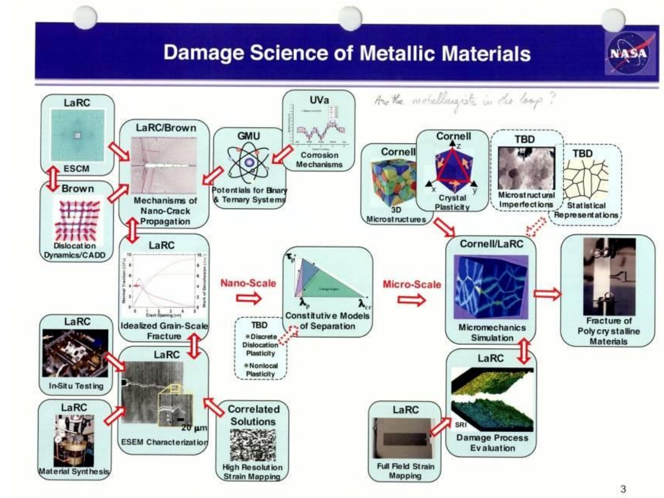
Computational Prototype Design is part of ADT

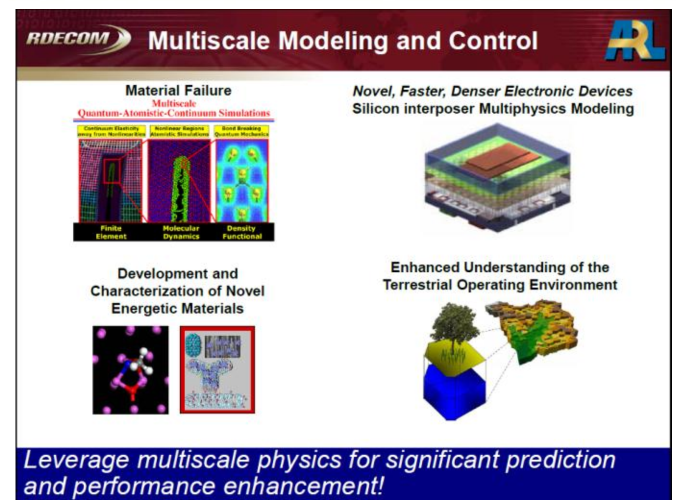


“Physics to Flight”

Collaborations related to Digital Twin

- **NASA -** **Ed Glaessgen/Steve Smith**
- **ARO -** **David Stepp**
- **MURI on Uncertainty –** **Fariba Fahroo**
- **Mathematics for Multi-Scale Modeling –** **Fariba Fahroo**
- **Transformational Computing –** **John Luginsland/Tatjana Curcic/Doug Smith**
- **MURI on Hybrid Structures –** **Joycelyn Harrison/Ali Sayir**
- **AFRL/RX ICMSE -** **Chuck Ward et al.**
- **AFRL/RQ Airframe Digital Twin –** **Eric Tuegel/Pam Kobyrn**
- **AFRL/RQ SSC -** **Ravi Chona et al.**
- **AFRL/RQ MSTC –** **Ray Kolonay et al**
- **ONR -** **Bill Nickerson**





Enabling Methodologies

Photoresponsive Liquid Crystal Polymer Networks: Future Generation Adaptive Materials
PI: Dr. Timothy White, AFRL/RX

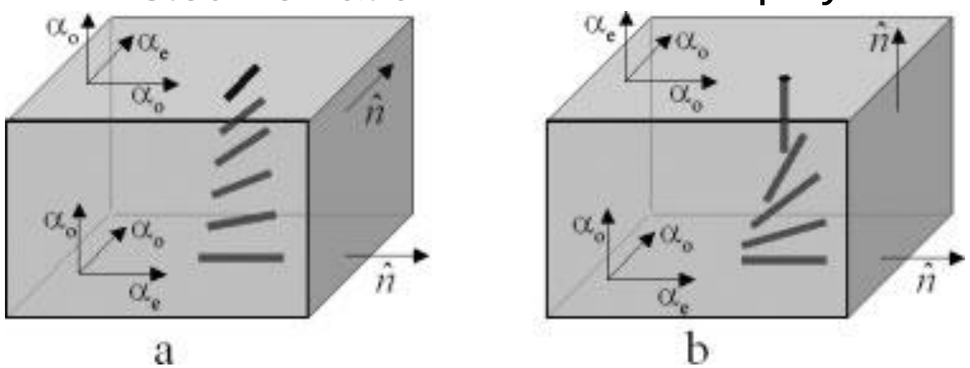
- **Goal is to develop and characterize *wirelessly* triggered stimuli-responsive polymeric materials capable of *rapidly reversible* planar and flexural-torsional shape adaptations exhibiting both shape-restoring (muscle like) and shape-retaining (shape memory) behavior.**
  - ***Responsive liquid crystal polymer synthesis, development, and characterization for conventional, hierarchical (through thickness), and spatially ordered systems***
  - ***Baseline polymer physics: correlated thermo-mechanical and photo-mechanical analysis***
  - ***Development of spatially controlled adaptations***

Liquid Crystal Polymer Networks (LCNs)

The orientation of the nematic director can be spatially varied through the thickness.

Twisted nematic

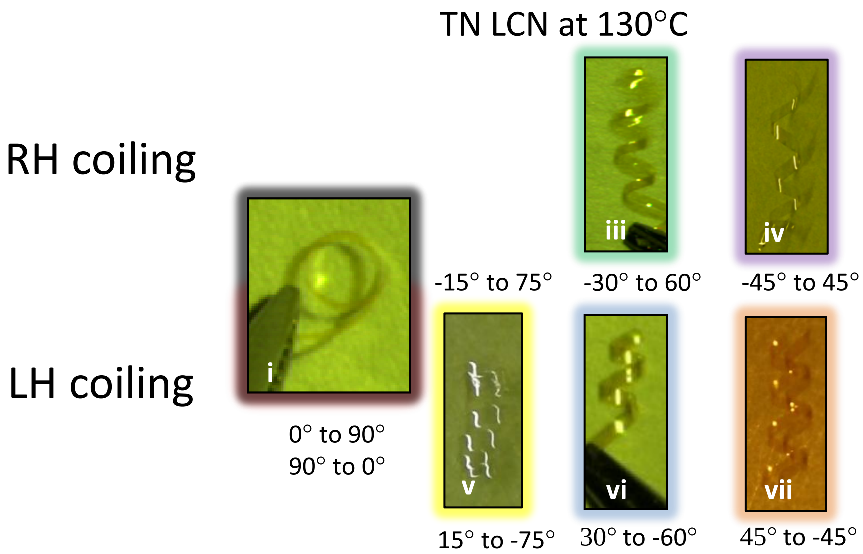
Splay

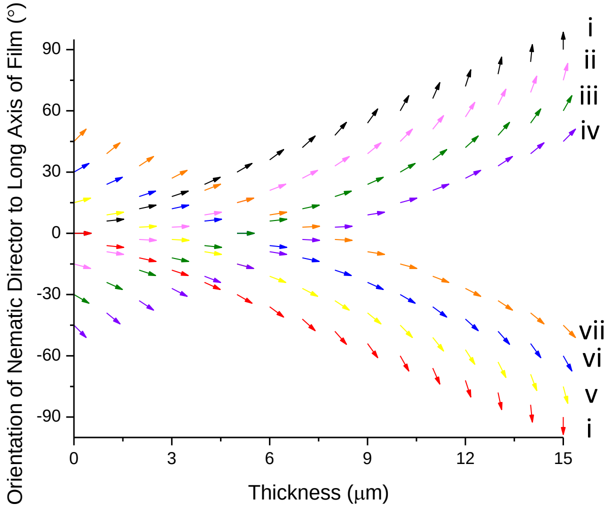


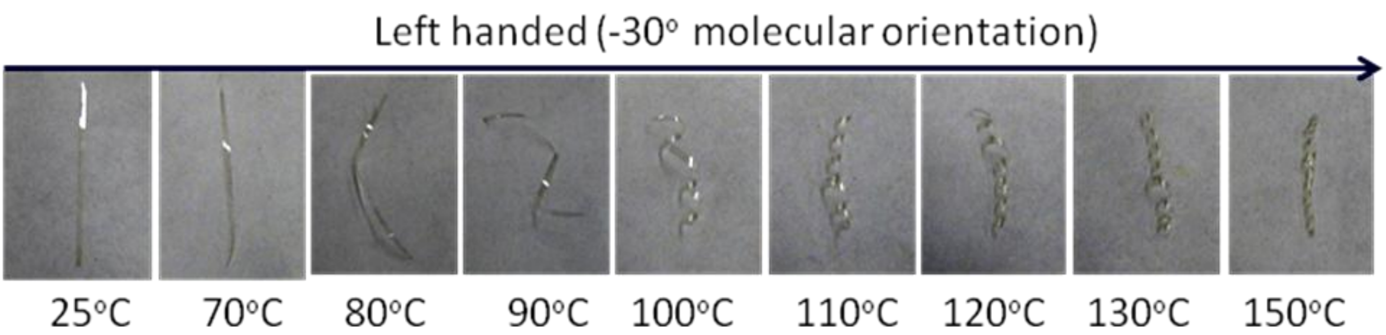
Broer et. al, Adv. Funct. Mater., 2005;
Eur. Phys. J. E, 2007.

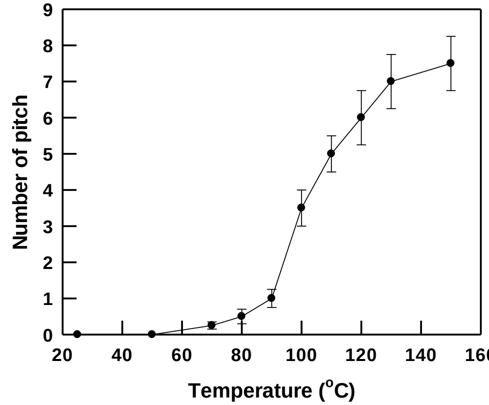
The resulting mechanical response is an interplay between the geometry of the film, the orientation of the liquid crystalline director (e.g. uniaxial, homeotropic, twisted, or splay) within the film, and the input stimulus (heat, light, electric field).

Tuning the Shape – Varying Orientation and Temperature





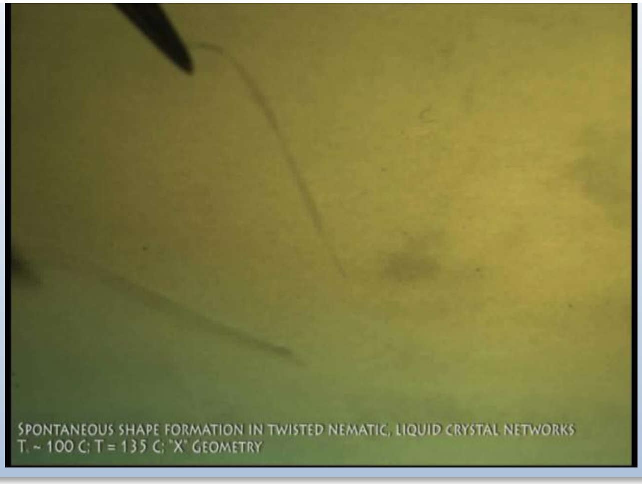


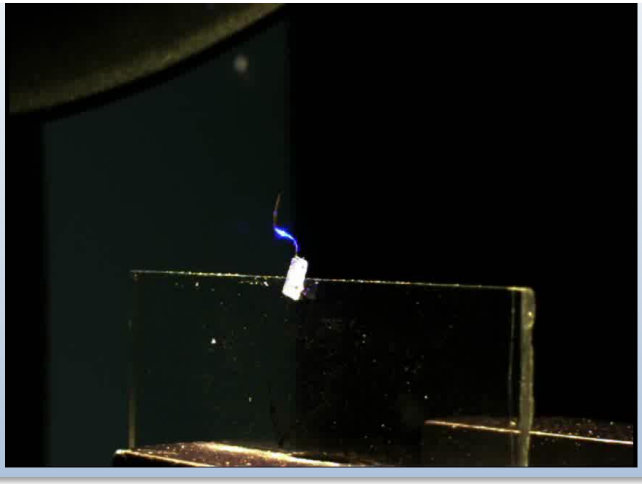


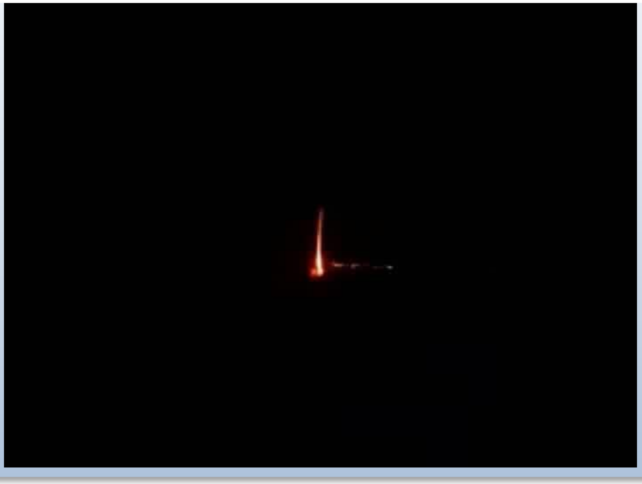
Lee/White et. al, Adv. Mater., 2012

TN

Populating material capability suite & exploiting design







Multi-Scale Structural Mechanics Summary

• Three core thrusts along with the integrating vision of a Virtual Twin Concept
  - Spans Exploratory and Anticipated Research for:
    - Novel Flight Structures
    - Multi-scale Modeling and Prognosis
    - Structural Dynamics

• Program focuses on core concepts of structural mechan
  - Computing
  - Predicting
  - Enabling

• Program is coordinated and actively collaborating with other government agencies and within AFOSR