



**Keynote Lecture -
The 8th Int'l Workshop
on Structural Health
Monitoring
14 September 2011,
Stanford, CA**

MULTIFUNCTIONAL DESIGN PERSPECTIVE FOR BIO-INSPIRED SYSTEMS ALLOWING AUTONOMIC RESPONSE

**B. L. (“Les”) Lee, ScD
Program Manager
Air Force Office of Scientific Research
Arlington, VA, U. S. A.**



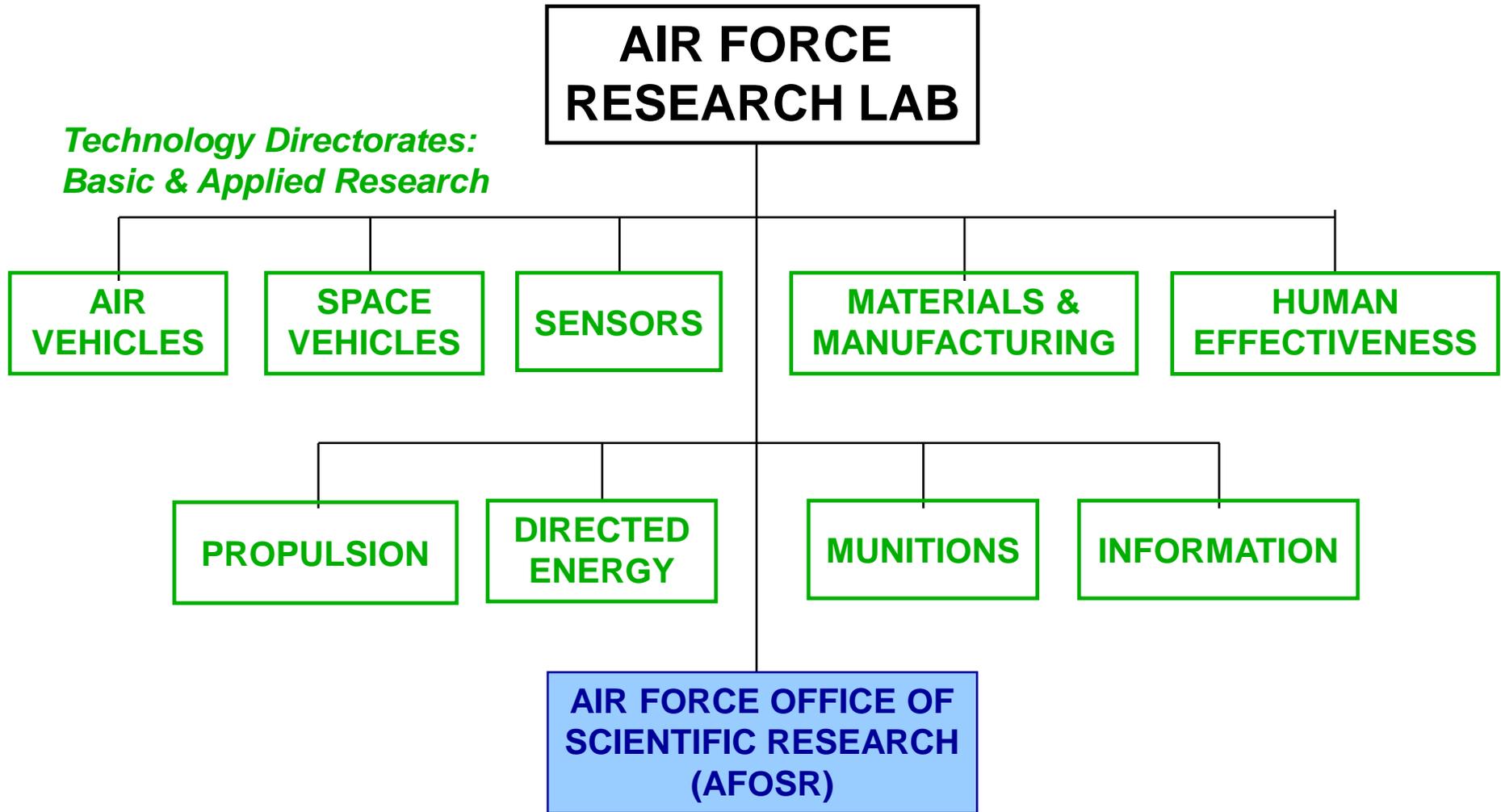
Acknowledgement



- **Conference Organizing Committee**
- **All PI's for AFOSR M^4 Program**
- **Scott White (U Illinois)**
- **Jim Thomas (Naval Research Lab)**
- **Brian Sanders (Air Force Combat Command)**
- **Bill Baron (Air Force Research Lab)**
- **Bruce LaMattina (Army Research Office)**
- **Shih-Chi Liu (National Science Foundation)**
- **David Banks (Boeing)**
- **Tom Hahn (UCLA)**



Representing Organization

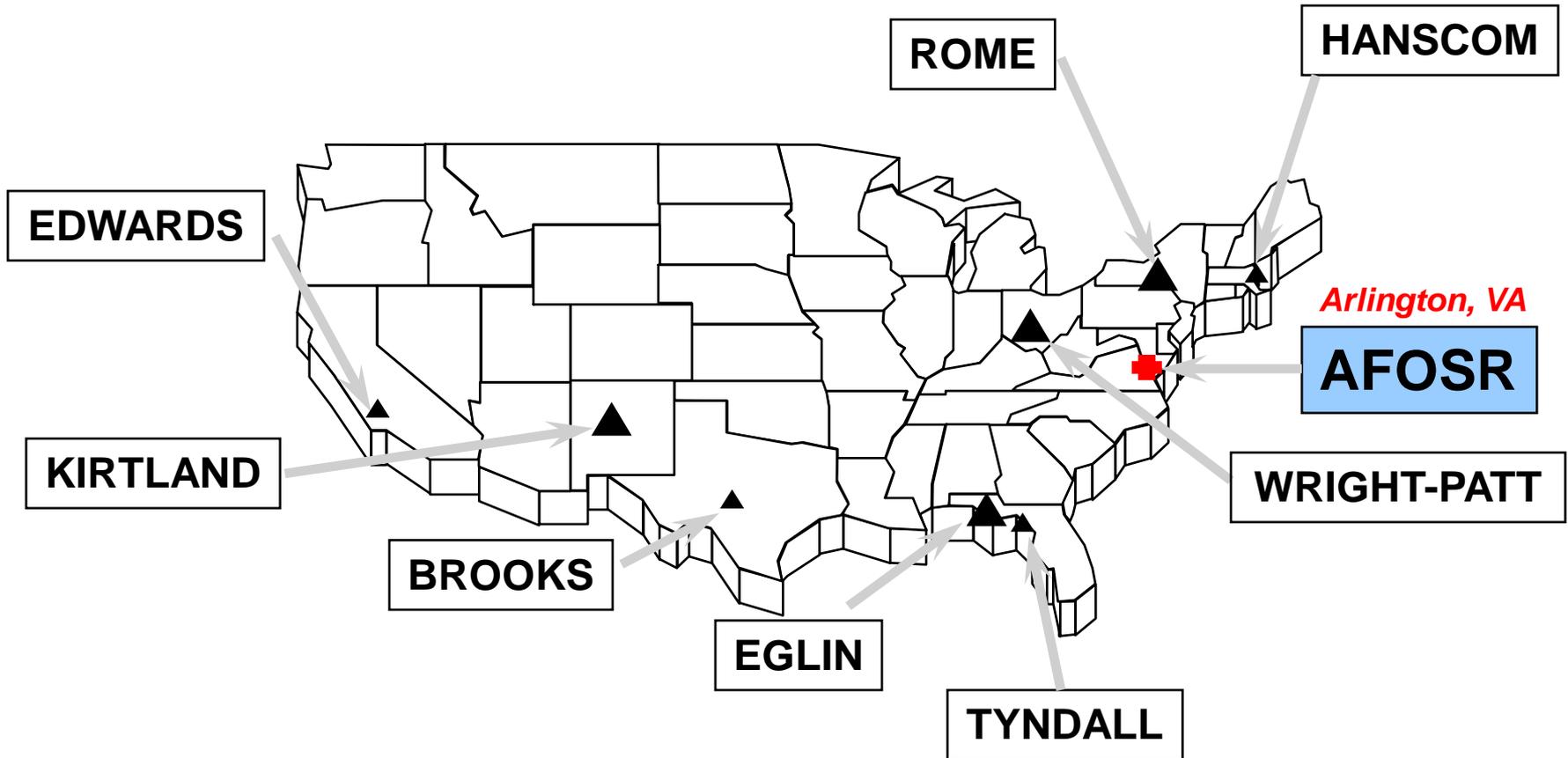


*Technology Directorates:
Basic & Applied Research*

Sole Manager of AF Basic Research



Location

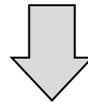




Representing Program

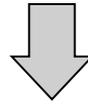


Mechanics of Materials



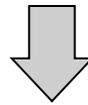
'97

Mechanics of Composite Materials



'99

Mechanics of Materials and Devices



'06

**Mechanics of Multifunctional Materials
and Microsystems**



AFOSR Portfolios Involved in Mechanics & Materials Sciences



- ***Mechanics of Multifunctional Materials & Microsystems (B. L. Lee)***
- ***Multi-scale Structural Mechanics & Prognosis (D. Stargel)***
- ***Flow Interaction & Control (D. Smith)***
- ***Aerothermodynamics & Turbulence (J. Schmisser)***
- ***Combustion & Diagnostics (J. Tishkoff)***
- ***Space Propulsion & Power (M. Birkan)***
- ***Thermal Sciences (K. Jata)***
- ***Electromagnetics (A. Nachman)***
- ***Dynamics & Control (F. Fahroo)***
- ***Computational Mathematics (F. Fahroo)***
- ***Low Density Materials (J. Harrison)***
- ***High Temperature Materials (A. Sayir)***
- ***Organic Materials Chemistry (C. Lee)***
- ***Molecular Dynamics & Theoretical Chemistry (M. Berman)***



AGENDA



- **Background**
- **Trends and Issues**
- **Sensory Networks**
- **Self-Healing & Self-Cooling**
- **Self-Powered Systems**
- **Future Plans**
- **Summary**



RESEARCH ISSUES

Guest Lecture by Dr. J. Thomas - 2008 AFOSR M⁴ Program Review



Multifunctional Design



- The objective of multifunctionality is **improvement** in system performance → Use **system metric(s)** to identify functions to combine and quantify gains.
- General Rules:
 - **Add functionality** to material with most complex function-physics.
 - Target unifunctional materials/components operating in the **mid-to-lower** functional performance regimes for multifunctional replacement.
 - Implement multifunctionality in the **conceptual stage** of system design.
- Performance of multifunctional material/component may **not** be as good as its unifunctional counterpart; irrelevant as long as system performance improves.
- Strong/weak **coupling** between the multiple function-physics may or may not exist and/or be important.
- Multifunctional potential depends on sub-system **interfacing** capabilities and function **compatibility**.

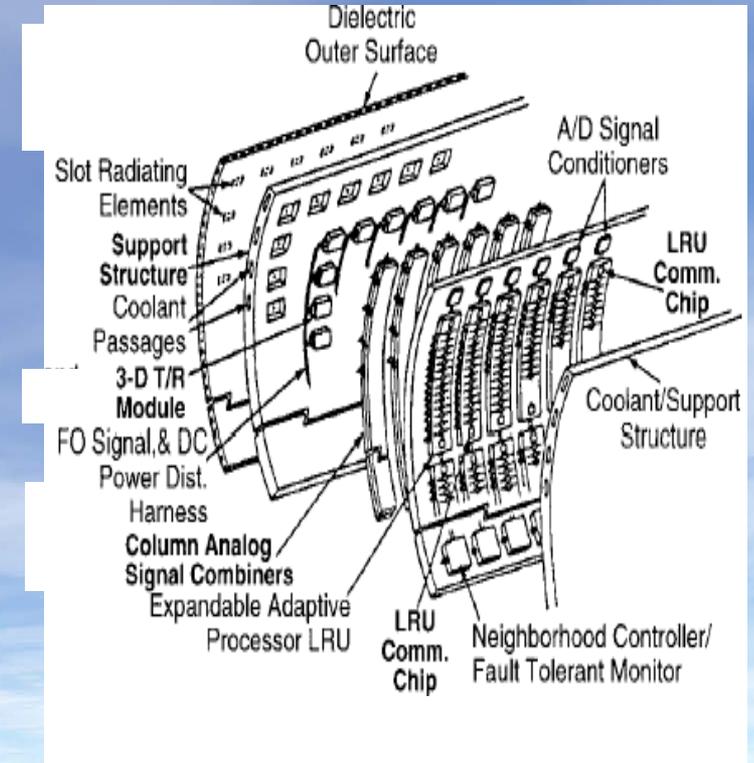


SENSOR PLATFORMS

Source: AFRL/RB



- Integrate antenna function into the structure
- **Antenna structure is load bearing**
- LO enabling
- Reduced maintenance vulnerability



RF-on-Flex
Conformal Load Bearing Arrays



SURVEILLANCE STRUCTURES

Source: AFRL/RV, Shape Change Inc., UCLA

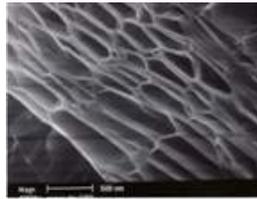


Shape memory alloy

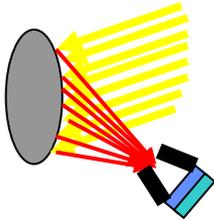


Smart Materials
Adaptive Structures

Graphite nanoplatelet

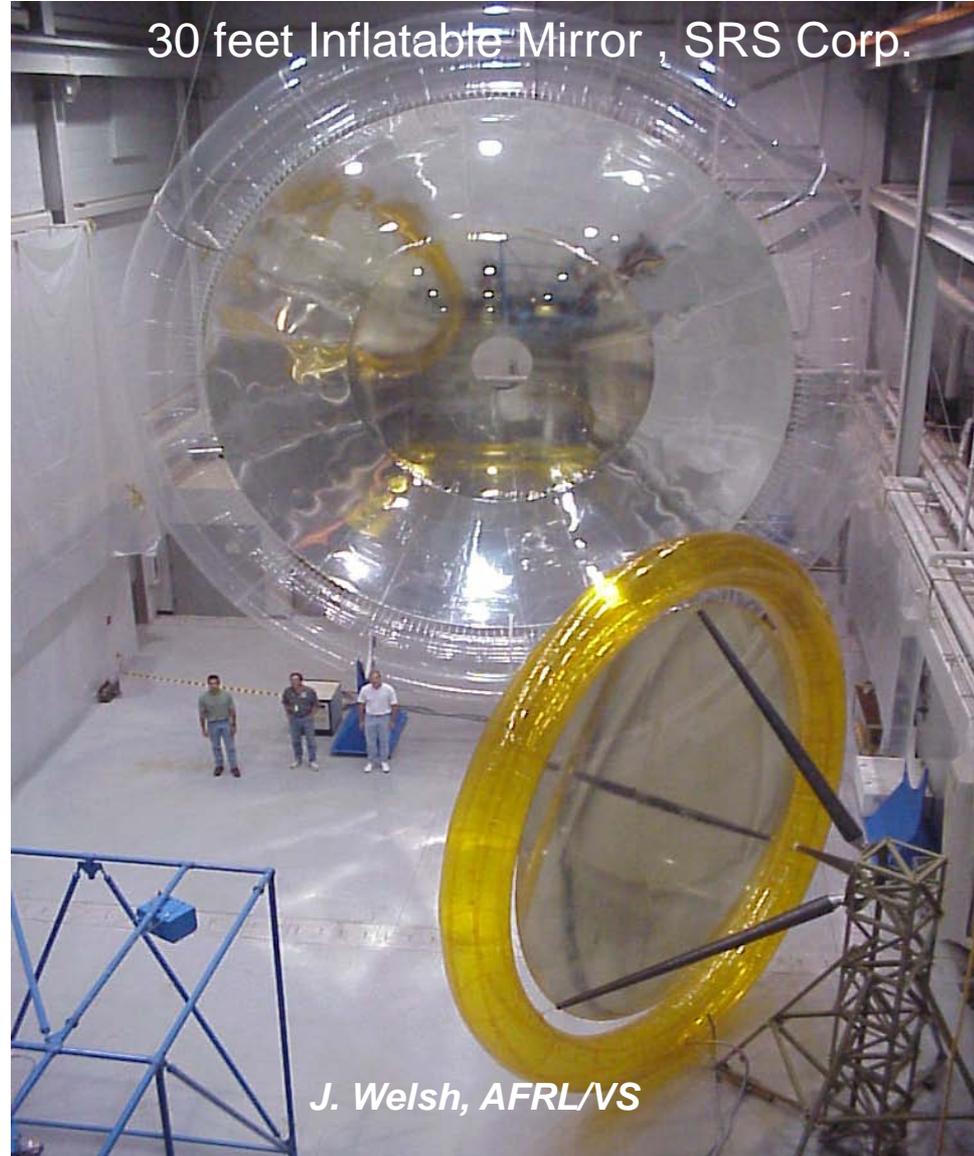


Self-Power Requirement



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30 feet Inflatable Mirror, SRS Corp.



J. Welsh, AFRL/VS

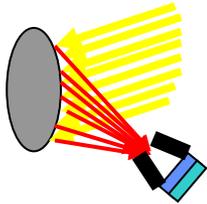


WHERE IS THE FIELD GOING?

Annual Review: 1 March 2005



- **Increasing Emphasis on Multifunctional Materials**
 - Structural integration of **electronic** devices
 - Combination of load-carrying capabilities with **functional** requirements (e.g. thermal, power)
 - **Adaptive, sensory** and **active** materials
 - Revolutionary concept of “**autonomic**” structures which sense, diagnose and respond for adjustment
 - **Hybridization** of materials and lay-up for complex requirements
- **Critical Needs for New Design Paradigm**
 - Physics-based **multi-scale** modeling
 - **Neural network** and information science
 - Design for **manufacture**





VISION

Annual Review: 18 March 2002



Biomimetics

**Design for Coupled
Multi-functionality**

Nano-materials

**Multi-scale
Model**

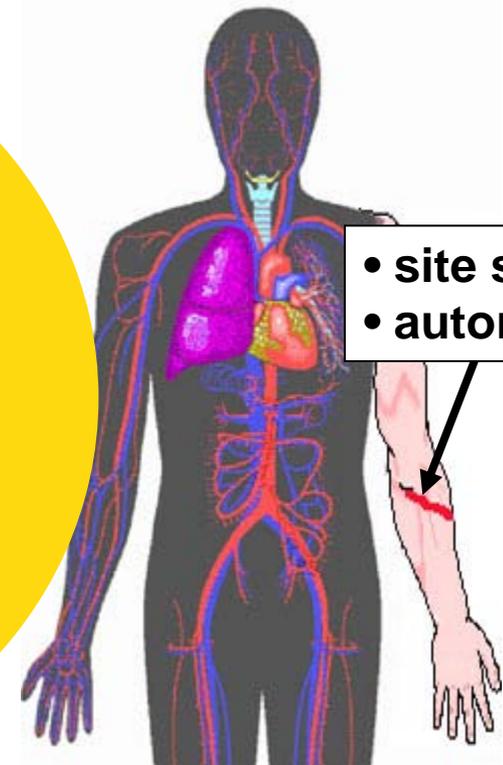
**Micro- & Nano-
Devices**

Manufacturing Sci

**Neural Network &
Information Sci**

AUTONOMIC AEROSPACE STRUCTURES

- **Self-Diagnosis**
- **Self-Healing**
- **Threat Neutralization**
- **Self-Cooling**



- **site specific**
- **autonomic**



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Biomimetics

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AUTONOMIC AEROSPACE STRUCTURES

- *Sensing & Precognition*
- *Self-Diagnosis & Actuation*
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 - **Self-Cooling**
 - *Self-Powered*



- **site specific**
- **autonomic**



BIO-INSPIRED SYSTEMS: BEYOND CURRENT VISION



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Scott White (UIUC)

Biomimetics

Design for Coupled
Multi-functionality

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Neural Network &
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**AUTONOMIC
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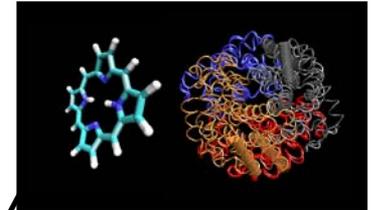
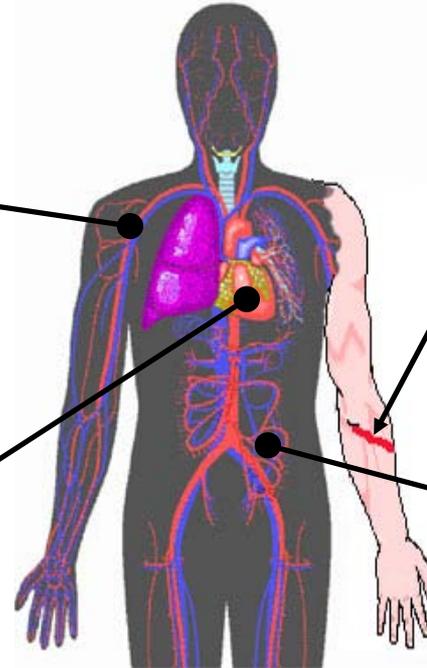
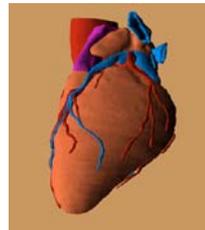


FUNCTIONS OF INTEREST



**Self-Regulating
Function**

Active Regulation



**Self-Generating
Function**

Mesoporous Networks





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- 
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*Energy from
Aerospace
Environ*



ENERGY MANAGEMENT: COLLABORATION WITH ARO/NSF



15-17 December 2004
Stanford University

AF/Army/NSF WORKSHOP ON MULTIFUNCTIONAL MATERIALS & STRUCTURES

Theme '04: Energy Harvesting & Storage

Workshop Chair:

Fu-Kuo Chang (Stanford Univ.)

Organizing Committee:

Julie Chen (NSF), **Co-chair**

Bruce LaMattina (ARO), **Co-chair**

B. "Les" Lee (AFOSR), **Co-chair**

David Banks (Boeing Phantom Works)

Brian Sanders (Air Force Research Lab)

Eric Wetzel (Army Research Lab)



Proposed: AFOSR/ARO MURI '06

MULTI-FUNCTIONAL DESIGN FOR
COMBINED LOAD-BEARING &
POWER GENERATION CAPABILITIES



Session I: Introduction (5 Presentations)

Session II: Energy Harvesting (3)

Session III: Structural Integration of Energy Harvesting

Russell Gaudiana (Konarka Technologies)

"Structural Integration of **Photovoltaic** Function"

Paul Clark (General Atomics)

"Structural Integration of **Thermionic** Function"

Matthew Malkin (Boeing)

"Structural Integration of **Piezoelectric** Function"

Dan Inman (VPI)

"Piezoelectric Materials for Structures"

David Ofer (Foster-Miller)

"High Strength Composite Fuel Cell Membranes"

Session IV: Structural Integration of Energy Storage

Jim Thomas (NRL)

"**Battery-Structure** Combination"

Bill Baron (AFRL)

"**Capacitor-Structure** Combination"

Ray Baughman (U Texas Dallas)

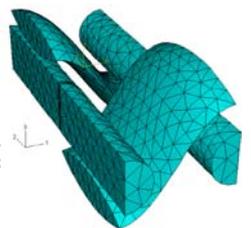
"Carbon Nanotube Fibers Providing Energy"

Charles Lakeman (TPL Inc.)

"Microsupercapacitors"

Brian Berland (ITN Energy Systems, Inc.)

"**Multi-functional Fibers** for Power Storage"

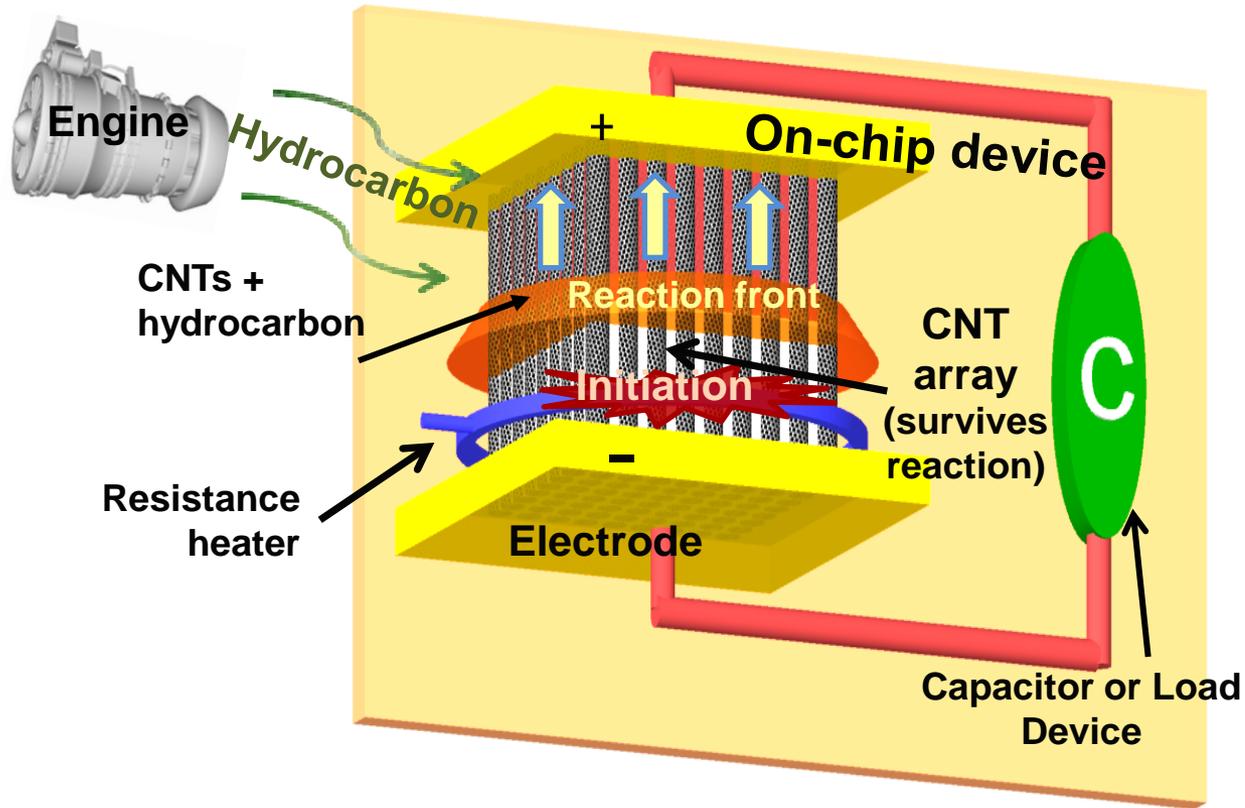


Session V: Sensing, Activation & Feedback (3)

Session VI: Breakout for Discussion



ENVIRONMENTAL HYDROCARBON HARVESTING (MIT: Strano)



Thermopower waves generate high-power electrical pulses

Due to high surface area carbon nanotube (CNT) arrays can **absorb hydrocarbon fuel** (e.g. octane) under ambient conditions.

Due to very high thermal conductivities, CNTs can **accelerate and direct a chemical reaction** in attached fuel, thereby producing **thermopower wave** of electrons.

Peak DC power as much as **20 W/g** – more than batteries – and can be smaller than 1 mm^3



ENERGY HARVESTING ON SPACECRAFT (Penn State: Bilén)



PROJECT SUMMARY

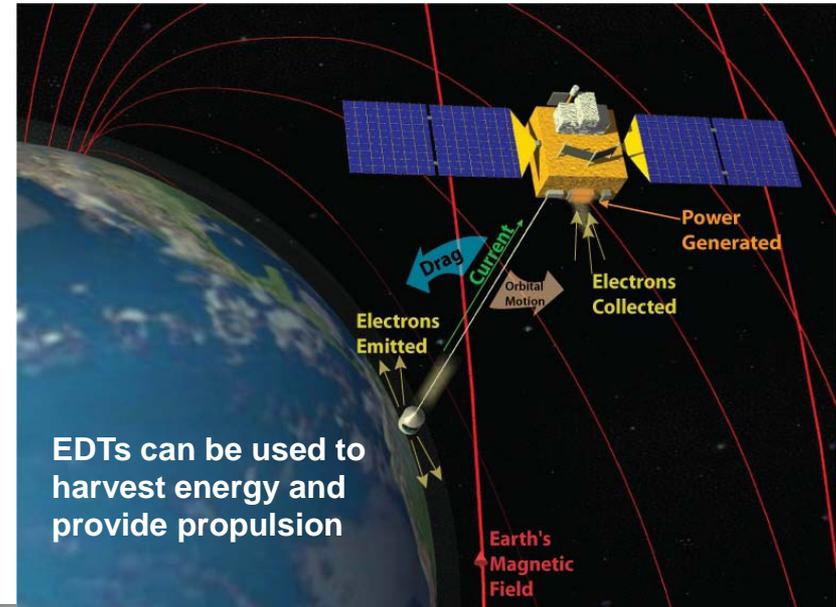
Objectives:

- Develop system concepts for use of Electrodynamic Tethers (EDT) on an array of spacecraft in variety of orbits and for various missions
- Address EDT performance parameters
- Evaluate various system components required
- Explore energy storage devices



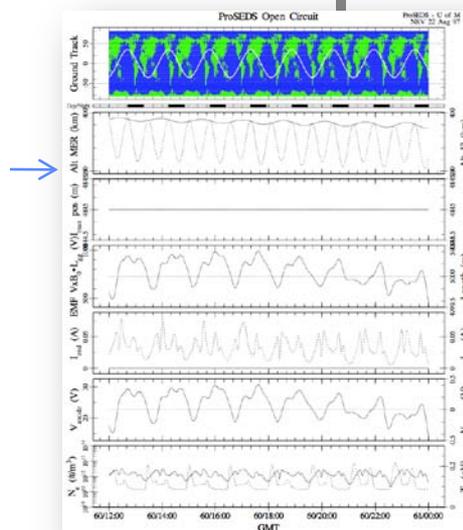
Team:

Sven Bilén, PI, and Jesse McTernan, Penn State
 Brian Gilchrist, Co-PI, and Iverson Bell, Univ. Michigan
 Rob Hoyt, Nestor Voronka, Co-Is, TUI, Inc.



APPROACH

- Explore EDT system architectures for energy harvesting and storage
- Employ tether simulation tools TeMPEST and TetherSim for verifying performance
- Develop and extend simulation tools to include energy harvesting modes and new components
- Define new architectures for various classes on missions and define precursor missions



ACCOMPLISHMENTS

- ChipSat system concept development and feasibility study
- CubeSat system concept development and solar panel comparison study
- Large spacecraft system concept development and voltage and current magnitudes study
- Work underway to implement an energy storage module for TeMPEST
- AIAA Space 2010 presentation paper



VISION: *EXPANDED*



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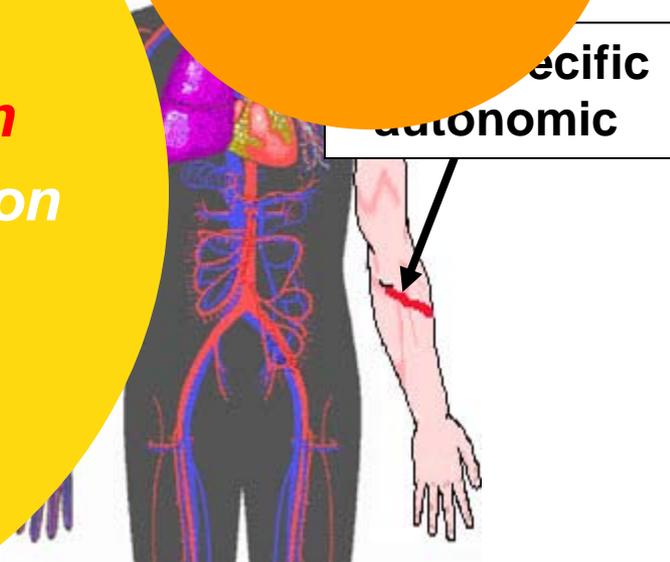
Manufacturing Sci

**Neural Network &
Information Sci**

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 - *Self-Powered*

*Reconfigurable
Systems*





MATERIAL FUNDAMENTALS FOR MORPHING

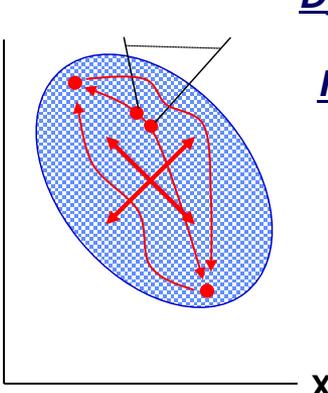


Rich Vaia & Jeff Baur (AFRL/RX)



Descriptive Variables of Active Response





Dynamic – reversible property changes ($\Delta X, \Delta Y, \dots$) with time (t), *magnitude*

Responsive – change ($\Delta X, \Delta Y, \dots$) with external stimuli (p), *range*

Tunable – controlled, reproducible increments of change ($\delta X, \delta Y, \dots$) with external control-loop, *precision*

Adaptive – performance (F) optimized for a change in external conditions with minimal control-loop required, *programmed, inherent, smartness*

$\Delta X, \Delta Y$ large

small p \rightarrow
large $\Delta X, \Delta Y$

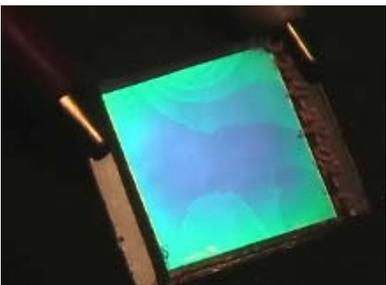
$\delta X \ll \Delta X$

$F(\Delta X(p), \Delta Y(p))$

Responsive



Tunable



Adaptive



4/20/01 3:14 PM



Design by Nature: BONE REMODELING



Resorption vs **Ossification**; 4~20% renewal per year;
Subjecting a bone to **stress** will make it **stronger**

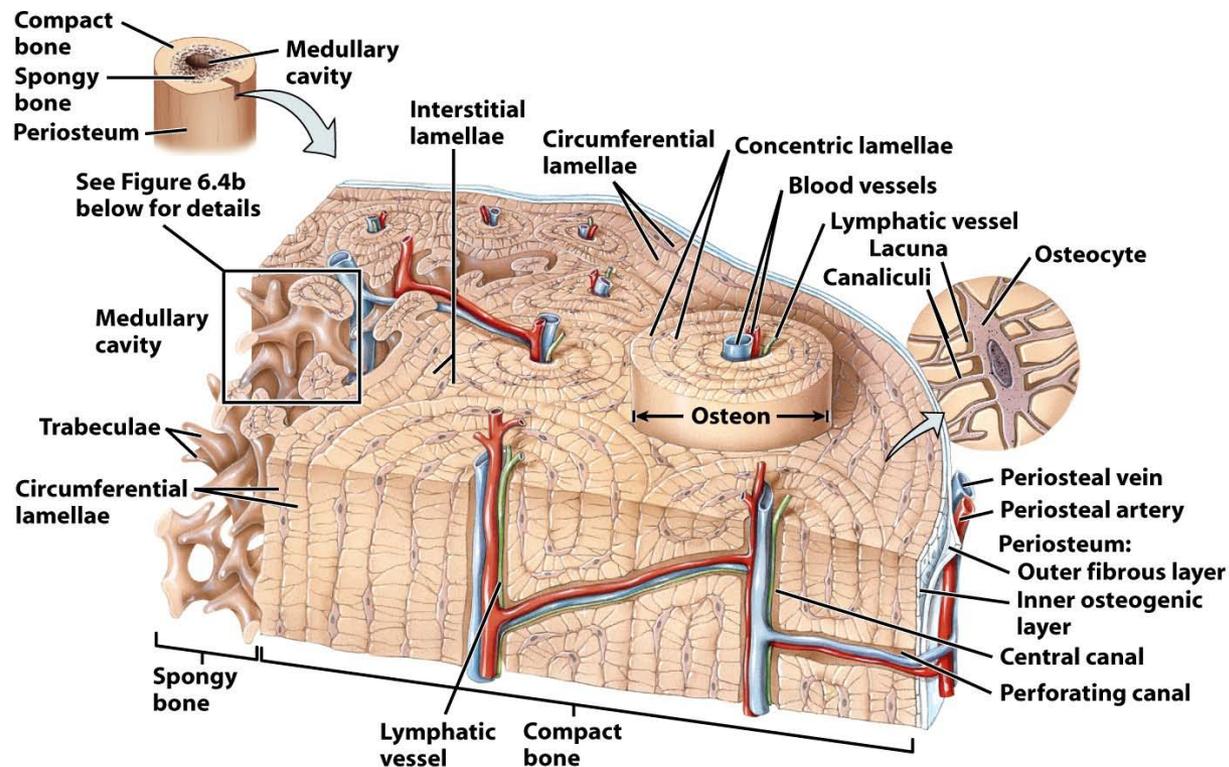
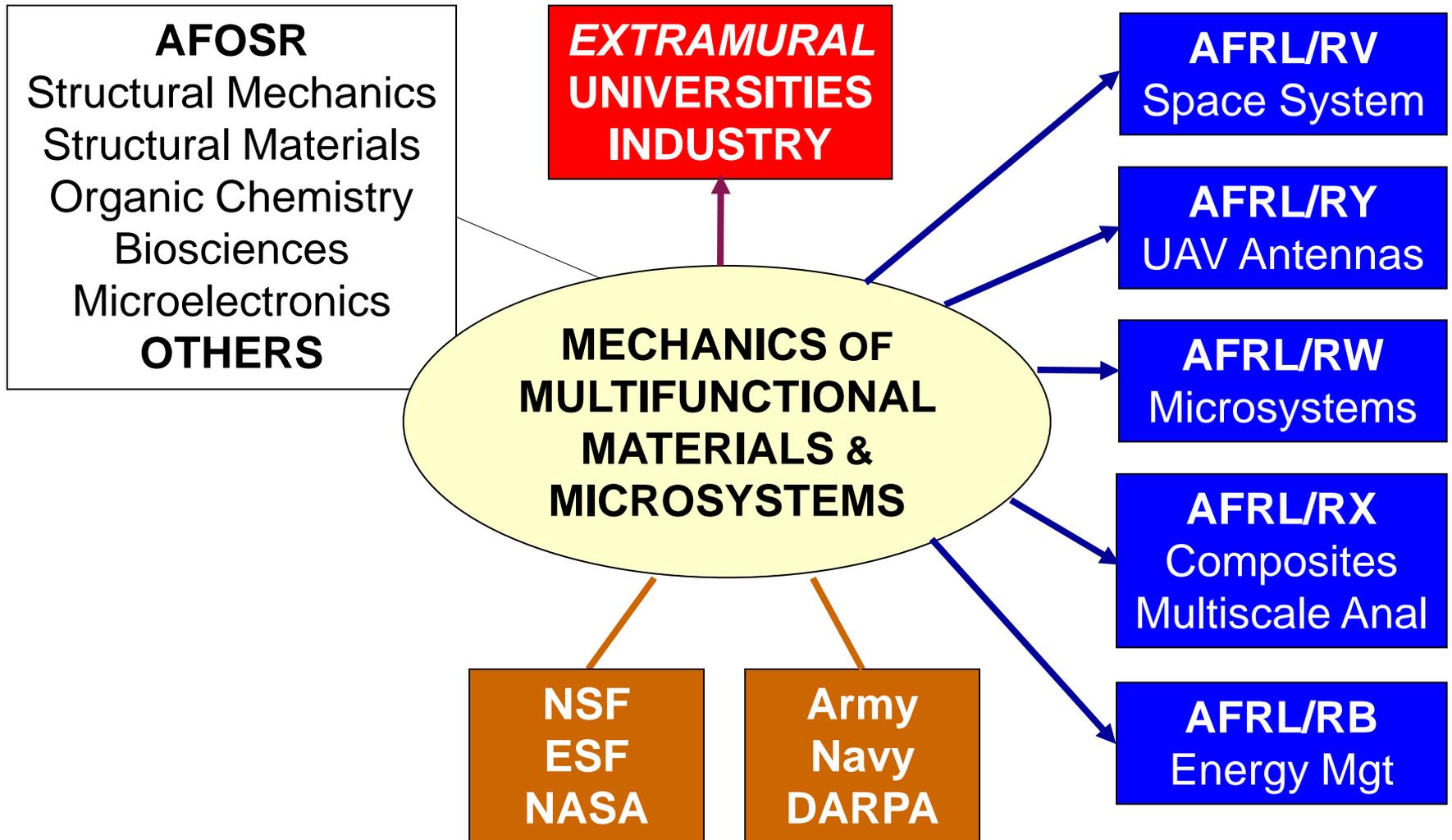


Fig. 6-4a Anatomy and Physiology: From Science to Life © 2006 John Wiley & Sons

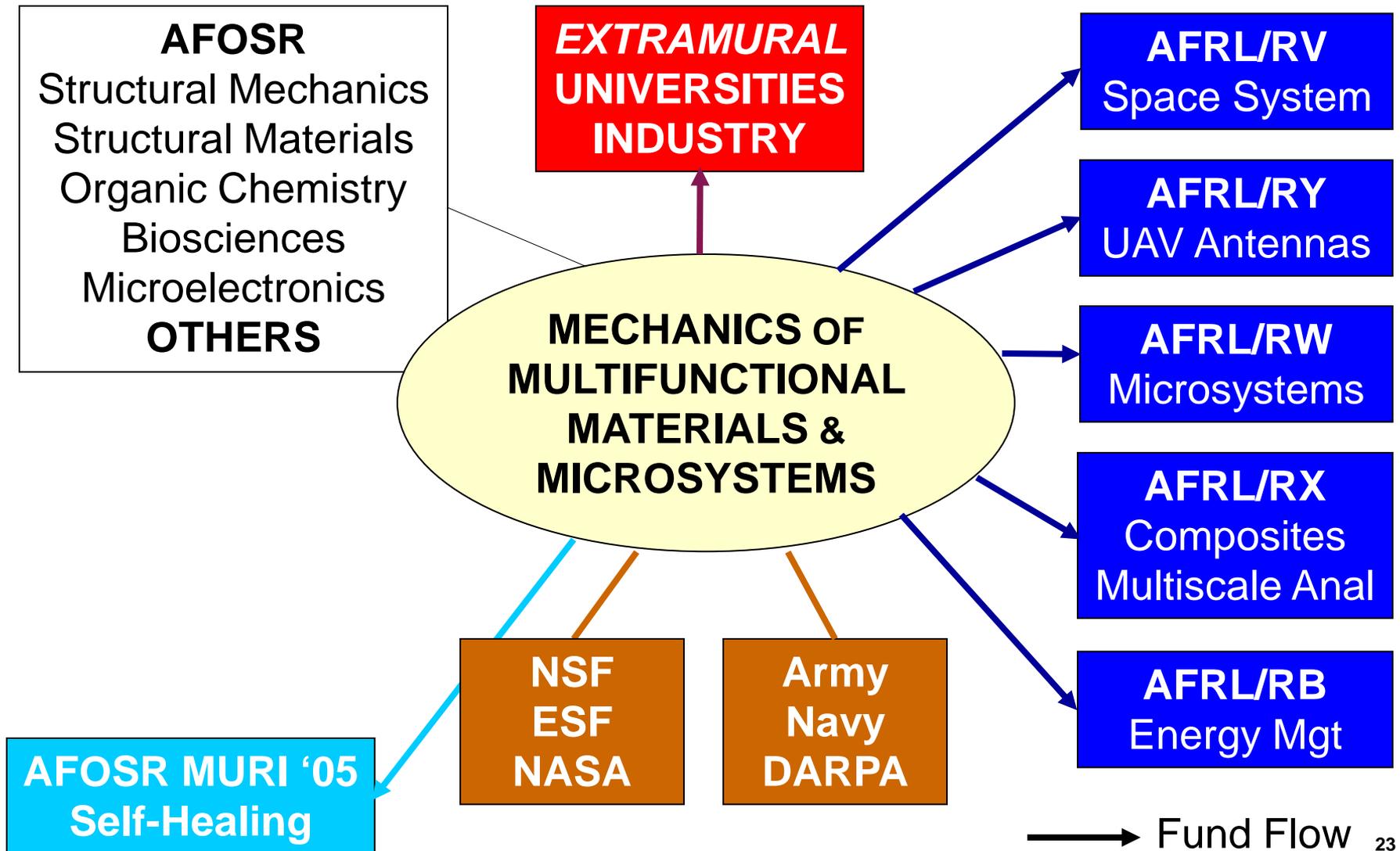


PROGRAM INTERACTION



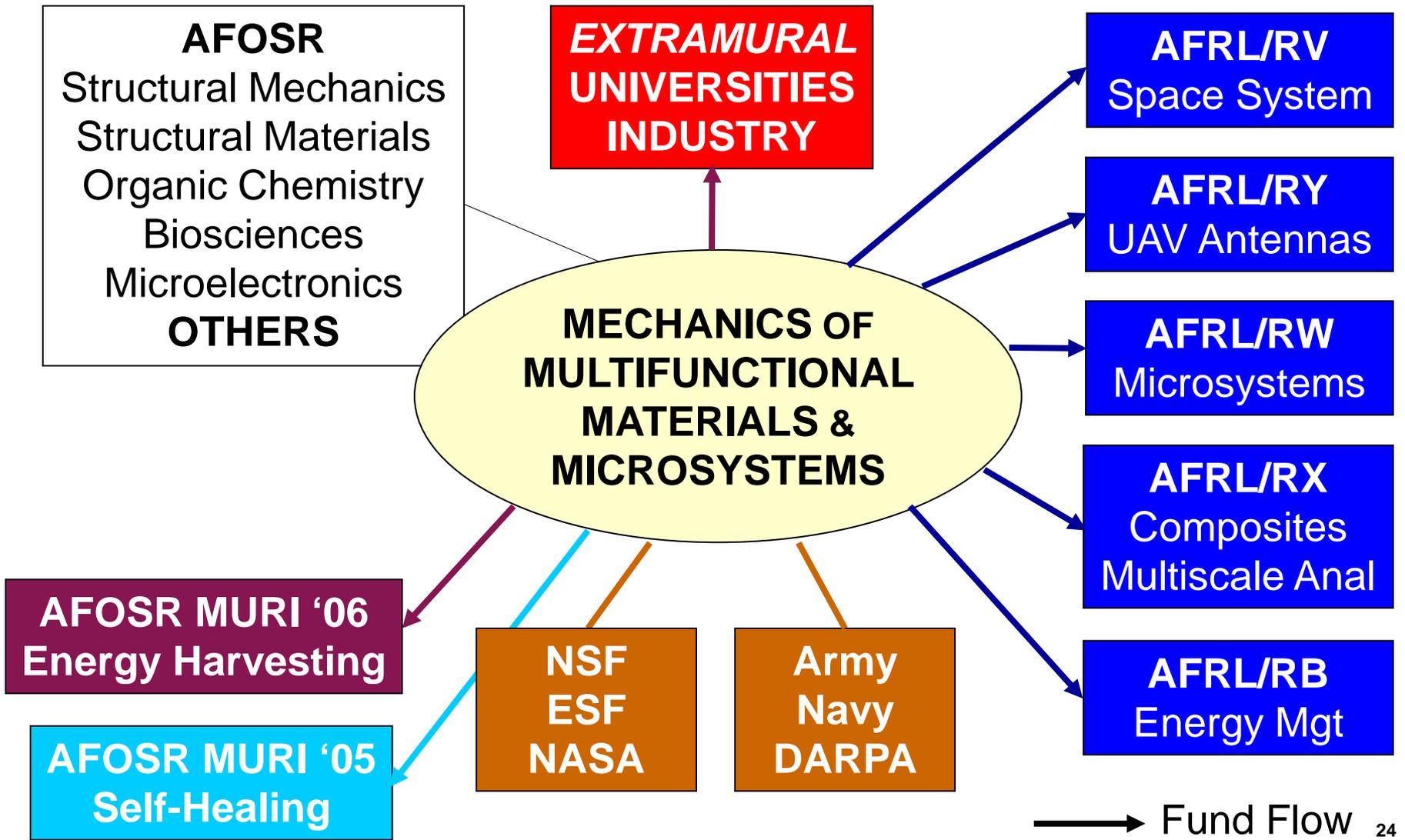


PROGRAM INTERACTION



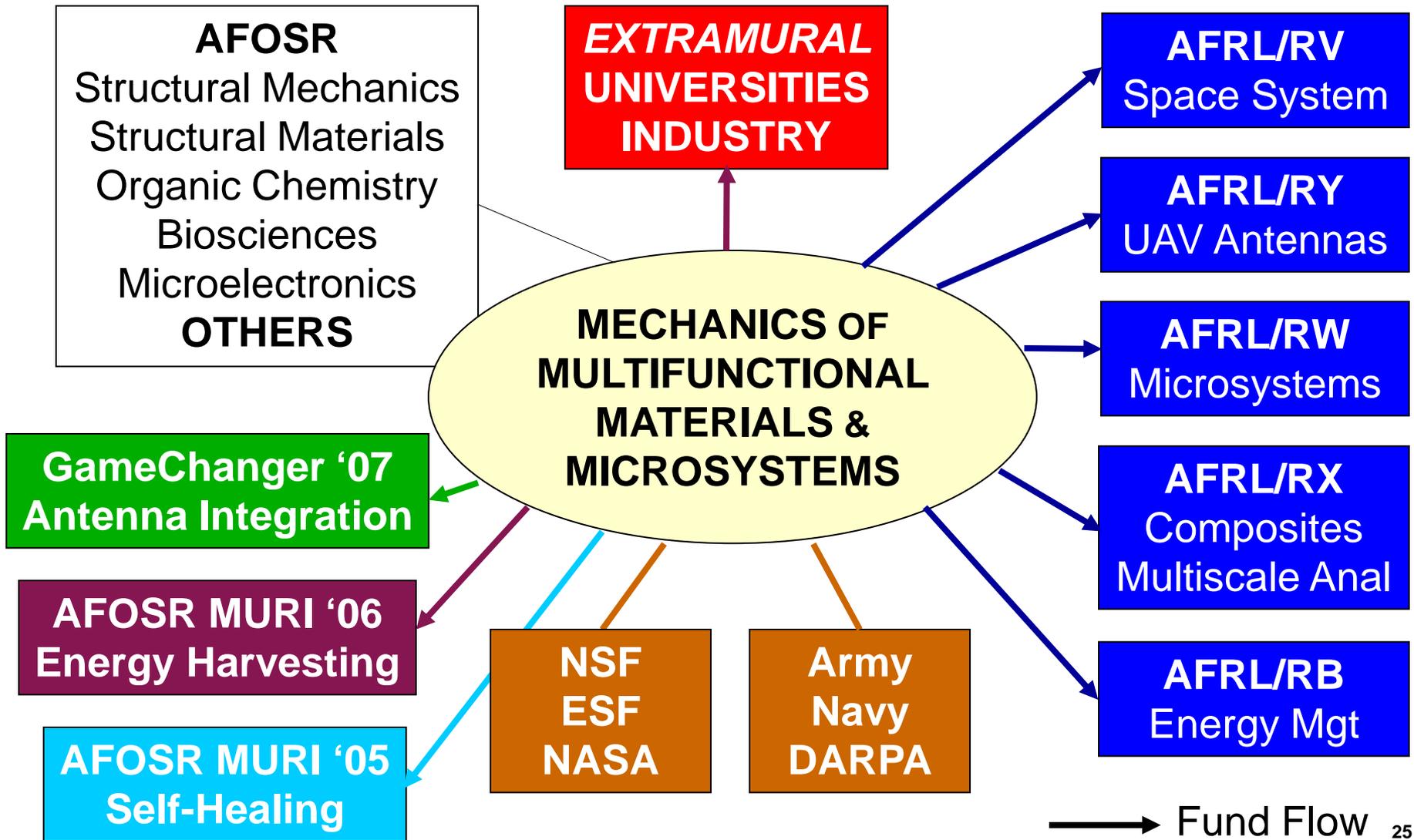


PROGRAM INTERACTION



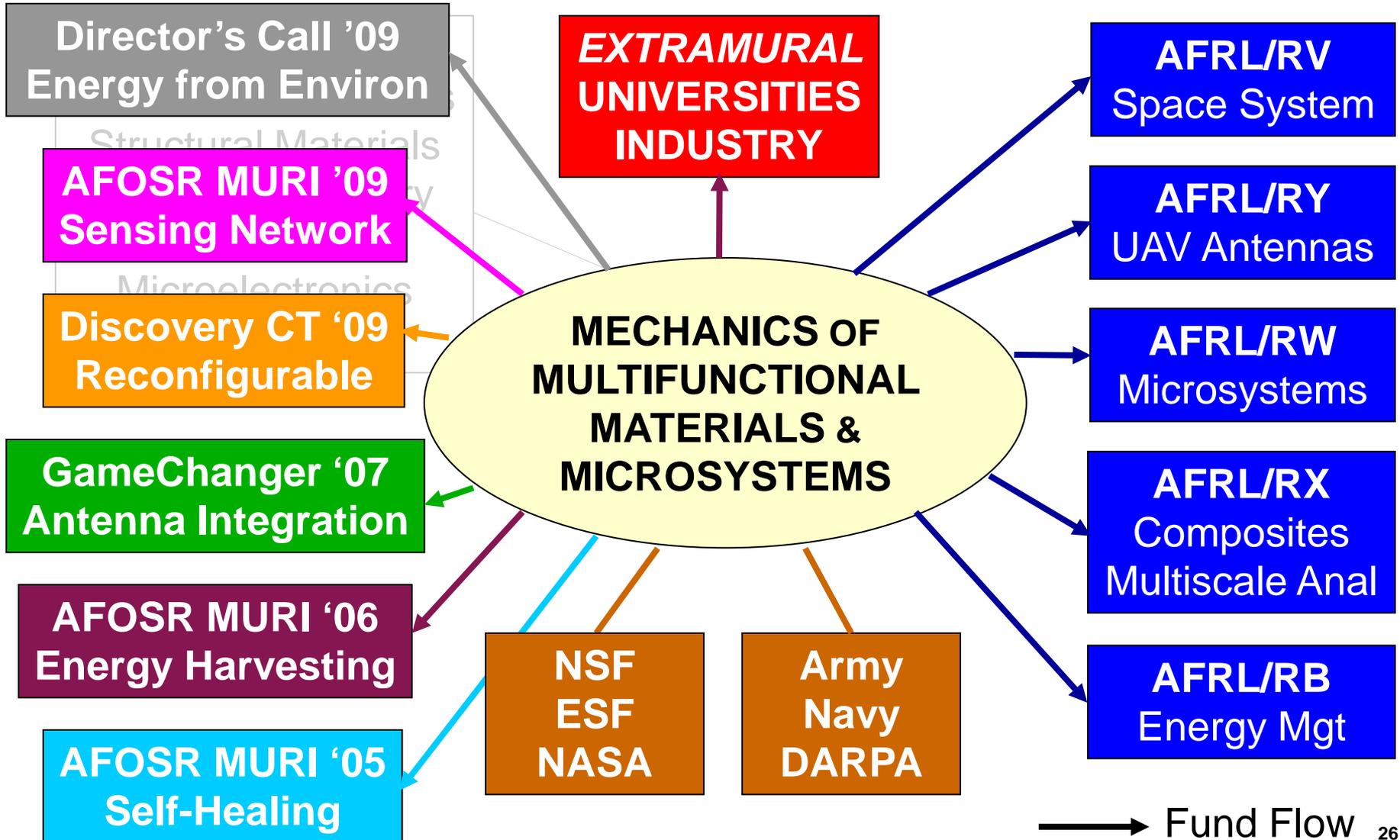


PROGRAM INTERACTION





PROGRAM INTERACTION





University Center of Excellence: HIGH-RATE DEFORMATION PHYSICS OF HETEROGENEOUS MATERIALS

OBJECTIVES:

- (a) To establish the University Center of Excellence to support DoD-focused research and education needs in modeling, measuring and understanding the **“high-pressure, high-strain-rate” physics** of heterogeneous materials (*i.e. impact loading at rates up to kilometers per sec or extremely rapid rates of energy deposition*),
- (b) To identify and better understand new basic research concepts involving the design of **“next generation” heterogeneous materials** with novel properties and the applications they enable,
- (c) To benchmark and lay a solid scientific background for the **future generation of material practitioners** via the intentional convergence of pertinent experimental, mathematical and theoretical capabilities.



VISION: *EXPANDED*



Biomimetics

**Design for Coupled
Multi-functionality**

Nano-materials

**Multi-scale
Model**

**Micro- & Nano-
Devices**

Manufacturing Sci

**Neural Network &
Information Sci**

AUTONOMIC AEROSPACE STRUCTURES

- ***Sensing & Precognition***
- ***Self-Diagnosis & Actuation***
 - ***Self-Healing***
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 - ***Self-Cooling***
 - ***Self-Powered***

***Reconfigurable
Systems***

***Specific
Autonomic***

***High-Rate
Deformation
Physics***



Transformational Opportunities



- **Self-healable** or **in-situ remendable** structural materials – *Quantum improvement in survivability of aerospace structures**
- Microvascular composites for **continuous self-healing** and **self-cooling** systems – ** & Ultimate thermal management*
- Structural integration of **energy harvest/storage** capabilities – *Self-sustaining UAV and hybrid-powered aircraft*
- Neurological system-inspired **sensing/diagnosis/actuation** network – *Autonomic state awareness in aerospace*
- Mechanized material systems and micro-devices for **reconfigurable** structures – *Neutralizing penetration threats*
- **Experimental** nano-mechanics – *Experimental verification of multi-scale analysis*



PROGRAM COLLABORATION



Emerging Frontiers in Research and Innovation (EFRI)



EFRI Topic Areas for FY 2009 / 2010

Two new research areas have been identified for the FY09 EFRI solicitation:

1. BioSensing & BioActuation
2. Hydrocarbons from Biomass

The research community should be considered for the Frontiers in Research and Innovation following website <http://www.nsf.gov/efri> topic idea along with the information provided.

TOPIC 1 BIOSENSING AND BIOACTUATION

- [Shih C. Liu](#)
[Yogesh B. Gianchandani](#)
[Leon Esterowitz](#)
[Rajinder Khosla](#)
[Eduardo Misawa](#)
[Lynn Preston](#)

BioSensing and BioActuation Proposed Research Opportunities/Challenges

1. Hierarchical Organization of Biological Systems

Uncover the unifying aspects underlying hierarchical bio-structures and bio-systems and use them for sensing and actuation; apply to new multi-scale and multi-functional sensor/actuator concepts.

2. Sensor Informatics Guided by Life

Create new knowledge that will be exploited in novel bio-inspired data mining and dynamic control, including capabilities to monitor, assess, and control living and engineered systems in sensor-rich environments.

3. Multifunctional Materials and Devices for Distributed Actuation and Sensing

Understand biological systems and mechanisms that lead to their ability to exhibit fault-tolerant actuation with a wide dynamic range, the production of practical means for producing artificial structures that exhibit similar behaviors, and their incorporation into useful engineered systems.

4. Forward Engineering & Design of Biological/Biomedical Components & Systems

Synthesize hybrid synthetic-living systems through systems-level integration of biological and engineered components that sense, actuate, compute, regenerate and efficiently allocate resources in order to achieve desired responses and functions.

THE 1ST "MULTIFUNCTIONAL MATERIALS FOR DEFENSE" WORKSHOP

Theme '10: Power and Energy

In conjunction with:

The 2010 Annual Grantees'/Contractors' Meeting for AFOSR Program on "Mechanics of Multifunctional Materials & Microsystems (M⁴)"

13-14 May 2010

Hyatt Regency Reston, Reston, VA

Workshop Co-Chairs:

- James Thomas (NRL)
 Eric Wetzel (ARL/WMRD)
 William Baron (AFRL/RBSA)

Organizing Committee:

- B.-L. ("Les") Lee (AFOSR), Co-Chair
 Bruce LaMattina (ARO), Co-Chair
 William Baron (AFRL/RBSA)
 Gregory Reich (AFRL/RBSA)
 William Nothwang (ARL/SEDD)
 Daniel O'Brien (ARL/WMRD)
 Eric Wetzel (ARL/WMRD)
 James Thomas (NRL)

BAA 06-028:

FY07 ARO MURI Topic #24

Self-healing Polymer Composites through Mechanochemical Transduction

Grant PI: [Jeff Moore \(UIUC\)](#)

PM: [David Stepp \(ARO\)](#)

Co-PM: [Douglas Kiserow \(ARO\)](#)



WORKSHOP: 2006/01/05, Chapel Hill, NC

KICK-OFF: 2007/10/03, Aberdeen, MD



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- **Self-Powered Systems**
- **Future Plans**
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VISION: *EXPANDED*



Acknowledgement:

Gregory Huff (Texas A&M)
Akira Todoroki (Tokyo Tech)
fu-Kuo Chang (Stanford U)*
Peter Peumans (Stanford U)*
Boris Murmann (Stanford U)*
Philip Levis (Stanford U)*
Andrew Ng (Stanford U)*
Rahmat Shoureshi (U Denver)*
Robert McLeod (U CO)*
Greg Carman (UCLA)*
Yong Chen (UCLA)*
Frank Ko (U Brit Columbia)*
Somnath Ghosh (Ohio St U)*^
John L. Volakis (Ohio St U)^
Roberto Rojas (Ohio St U)^
Stephen Bechtel (Ohio St U)^
Dick James (U MN)^
Max Shtein (U Mich)^
Nick Kotov (U Mich)^
Ben Dickinson (AFRL/RWGN)
Greg Reich (AFRL/RBSA)
Jeff Baur (AFRL/RXBC)

* MURI; ^ GameChanger

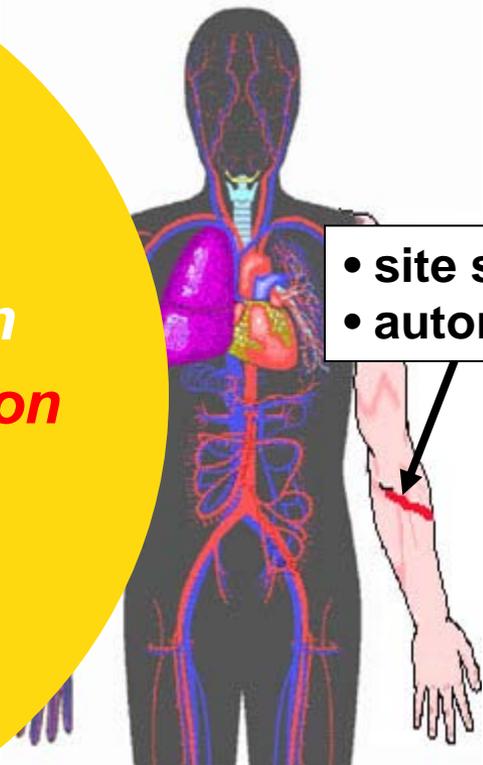
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AUTONOMIC AEROSPACE STRUCTURES

Sensing & Precognition

Self-Diagnosis & Actuation

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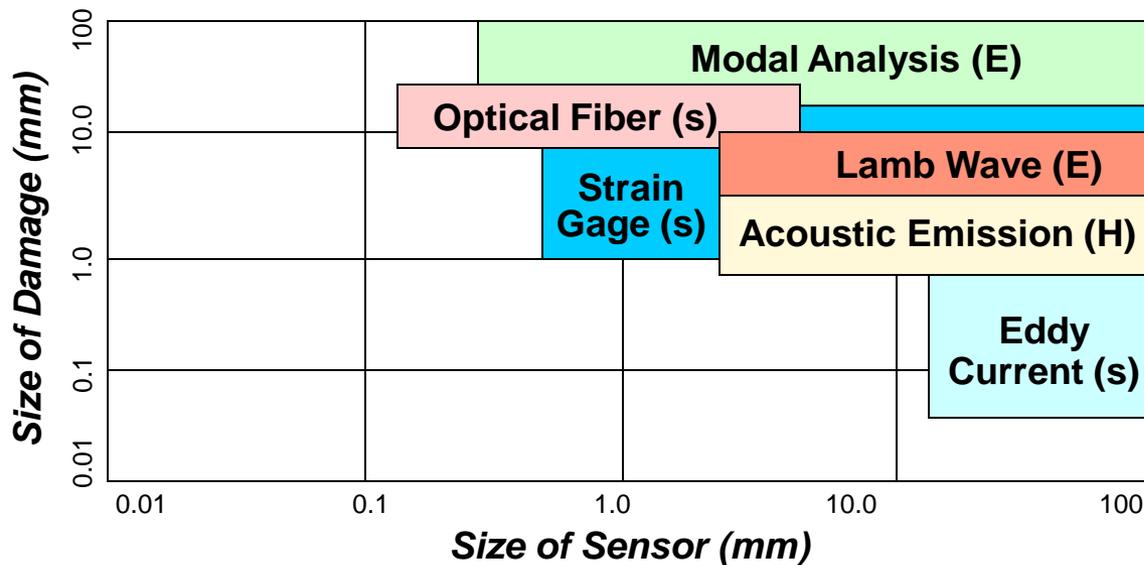
- site specific
- autonomic



Issue: SIZE OF SENSORS FOR HEALTH MONITORING

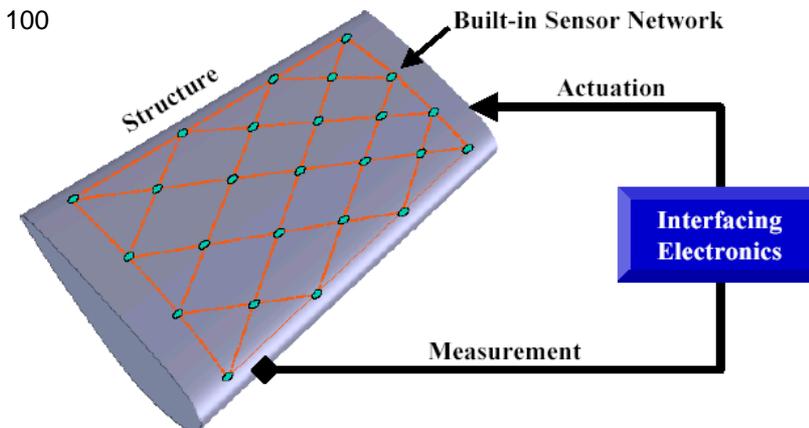


Size of Detectable Damage vs Sensor Size



GOALS:

- Improve reliability and safety
- Enhance structural performance
- Minimize unnecessary downtime
- Reduce maintenance cost
- Prolong structural life cycle

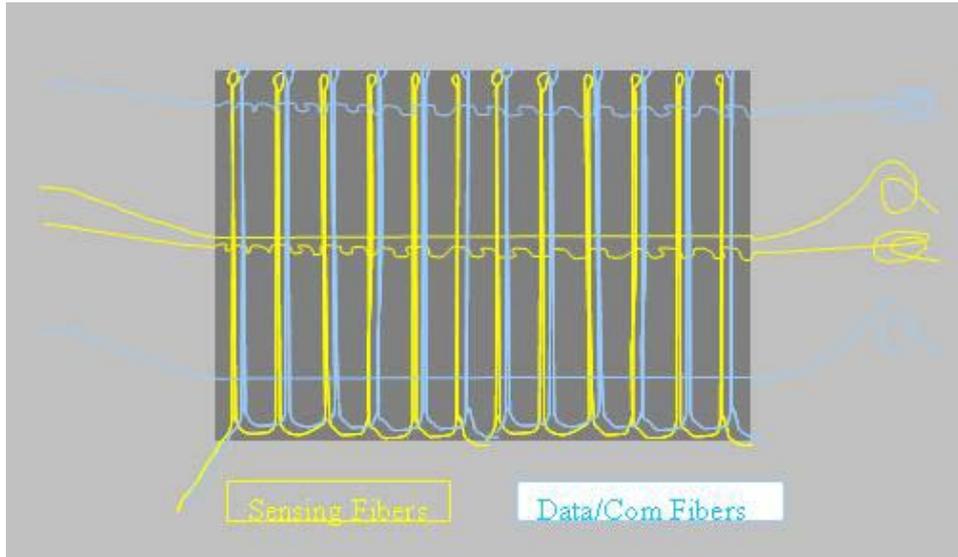




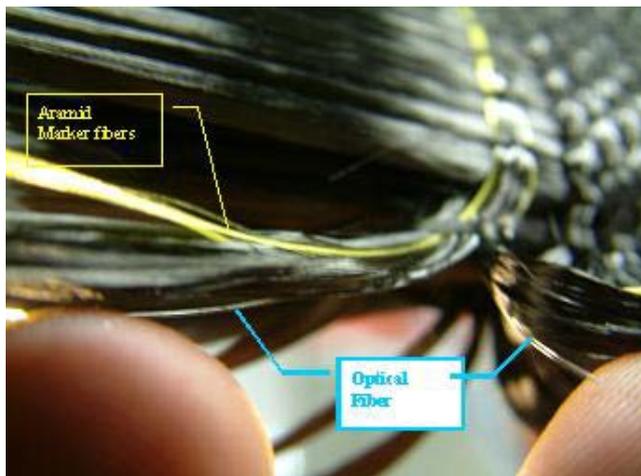
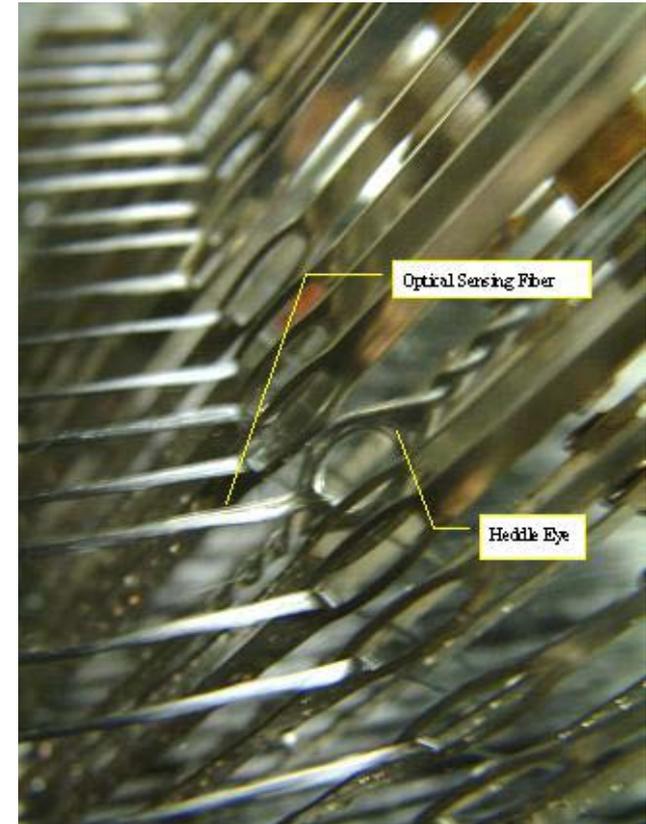
STTR: SENSOR-INTEGRATED COMPOSITES (*3Tex: Bogdanovich*)



Schematic of sensing fiber placement



Integration into Z-yarn



Optical fiber weft loops show entering and re-entering at the preform edge

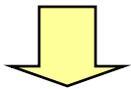
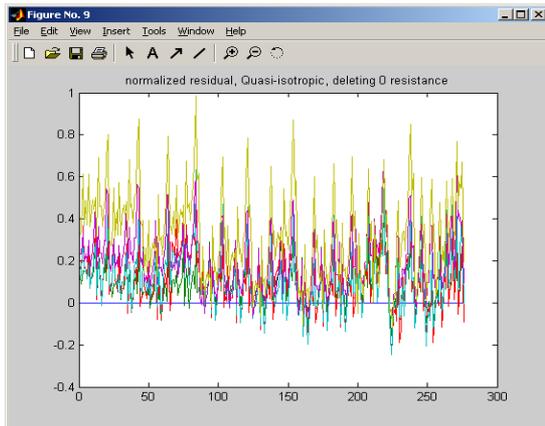




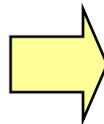
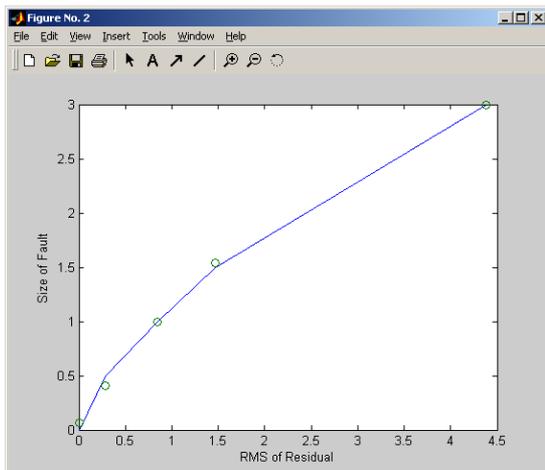
STTR: SELF-DIAGNOSIS OF COMPOSITES (ITI: Roemer)



Electrical Resistance Values

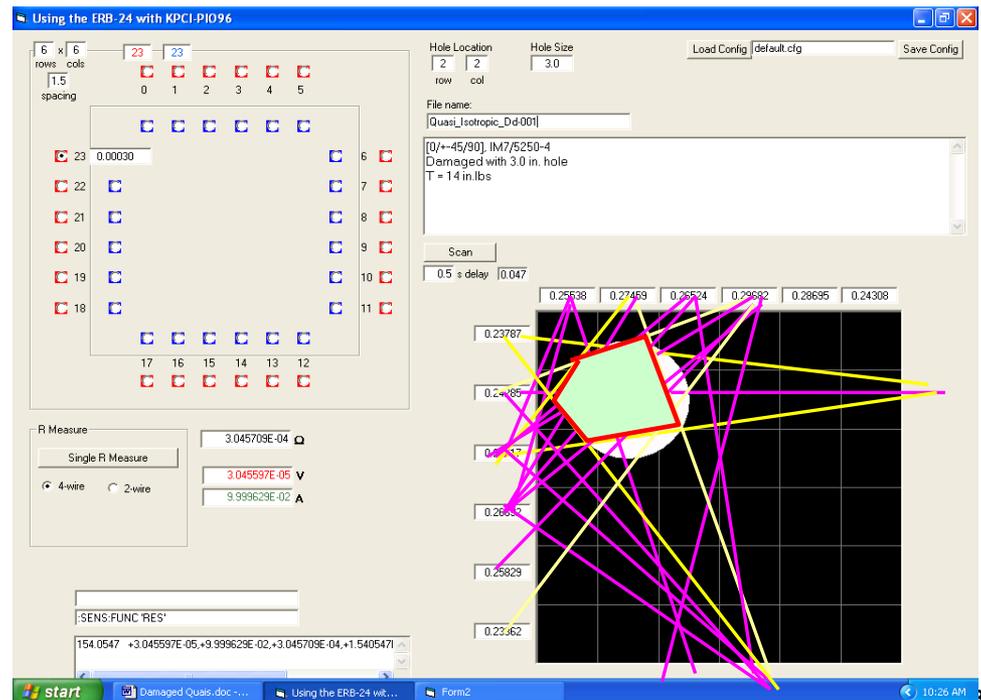


Neural Net Prediction of Damage Size



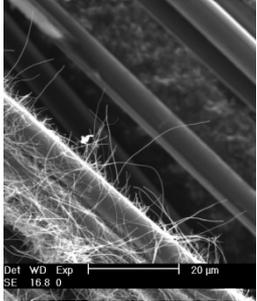
- Study the role of sensing geometries so that the **electrical response** can be correlated to the type, size and location of **localized damage** in CFRP.
- Develop autonomous damage detection software for efficient analysis of local failure mechanisms.

Automated Classification of Damage Size and Location



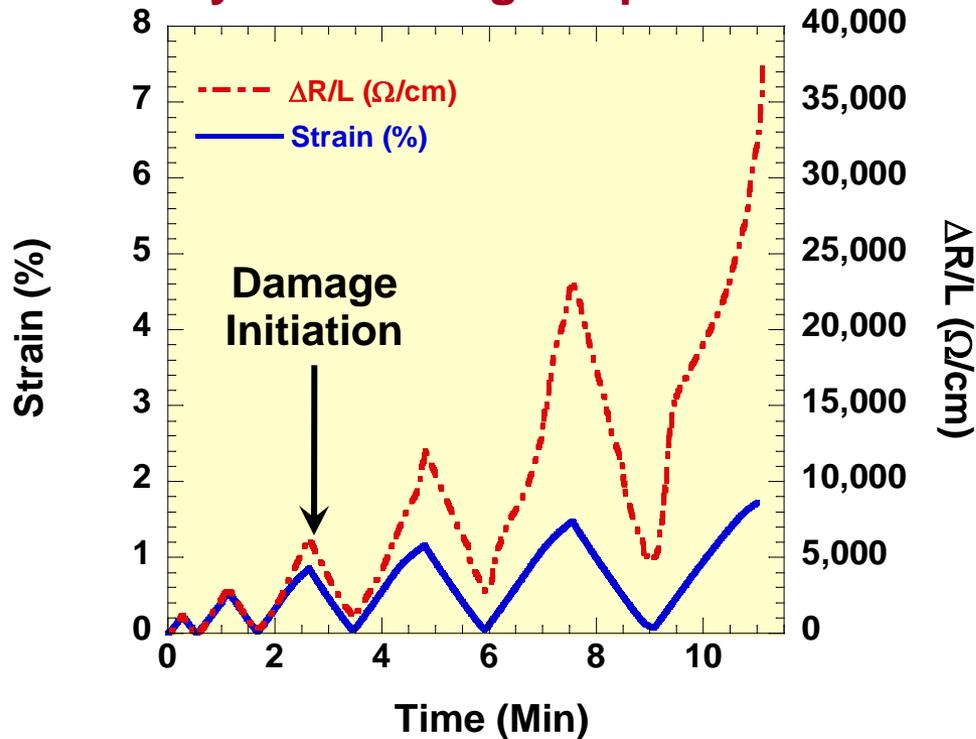


STTR/Core: CNT FOR DAMAGE SENSING (C Solution/U Del: Chou)

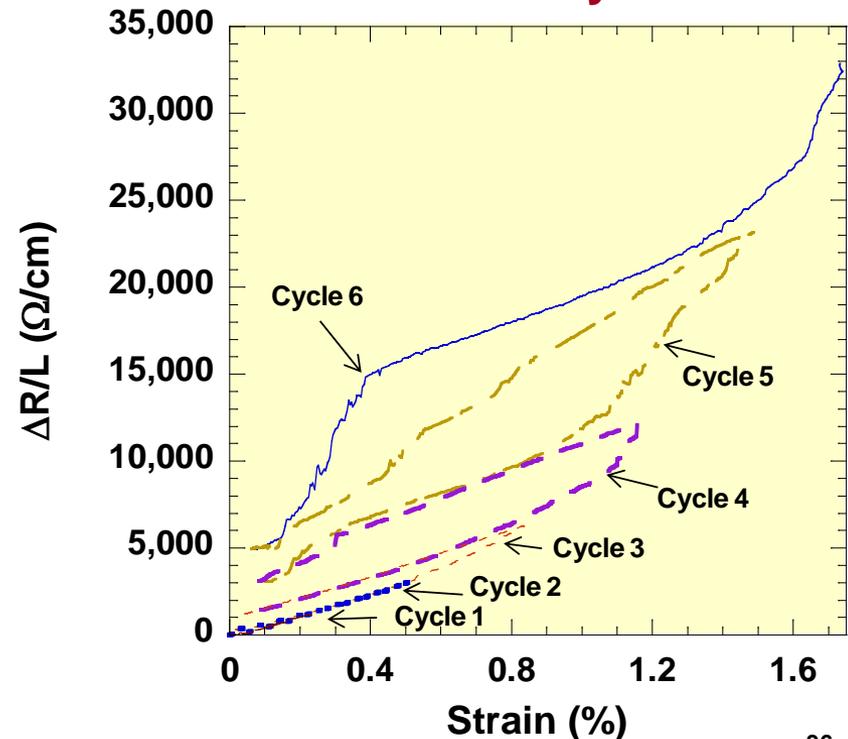


- Carbon nanotubes can penetrate matrix-rich regions surrounding reinforcing fibers and create an electrically percolating network. This enables unique opportunity for **in situ** sensing for strain and damage in structural composites.

Cyclic Loading Response



Resistance Hysteresis

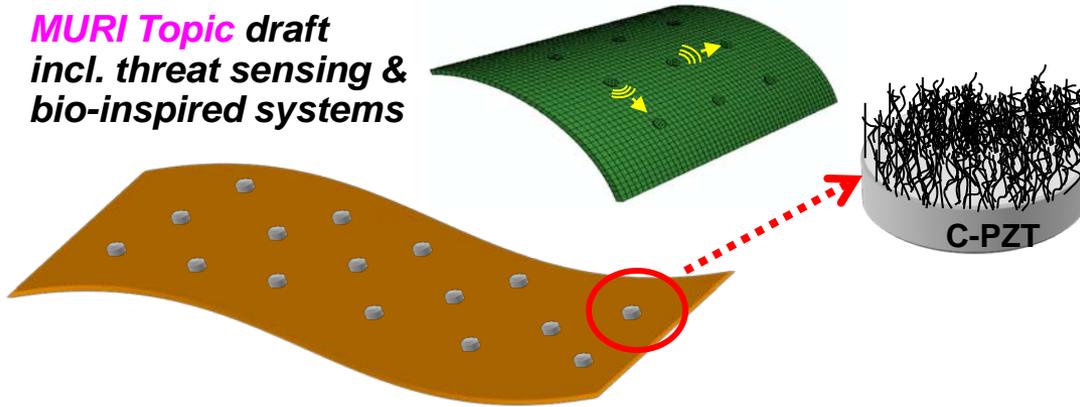




BUILT-IN SENSING NETWORK (Stanford U: Chang)



MURI Topic draft
incl. threat sensing &
bio-inspired systems

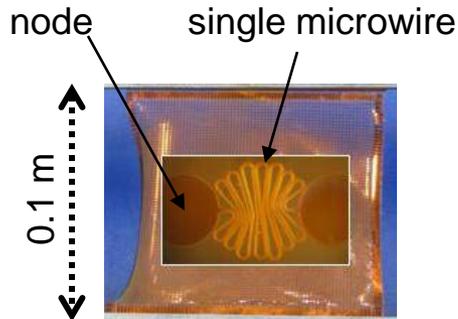


C-PZT Sensor:

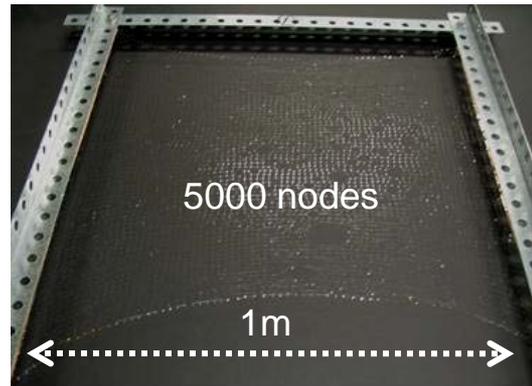
Fabrication of a PZT sensor with its surface coated with high density array of CNT as an electrode replacing standard silver paste coating

C-PZT Sensor Network:

Fabrication of stretchable form of high density array of C-PZT sensor network covering large area for sensing of internal damage



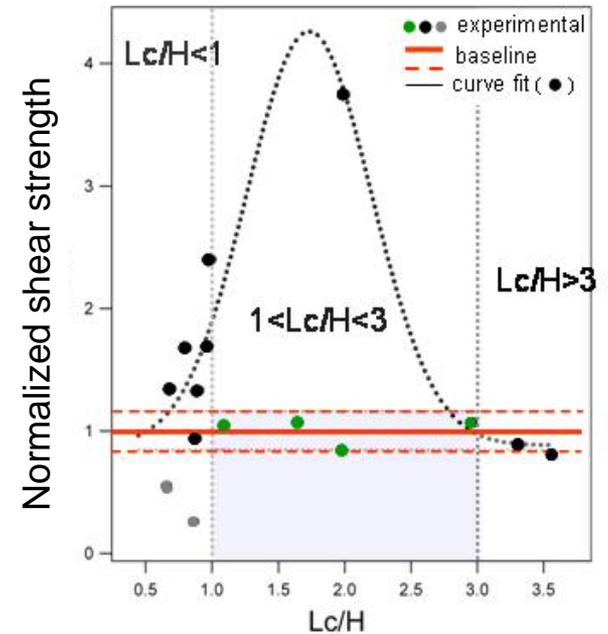
5000 Interconnected Nodes Before Stretching



After Stretching

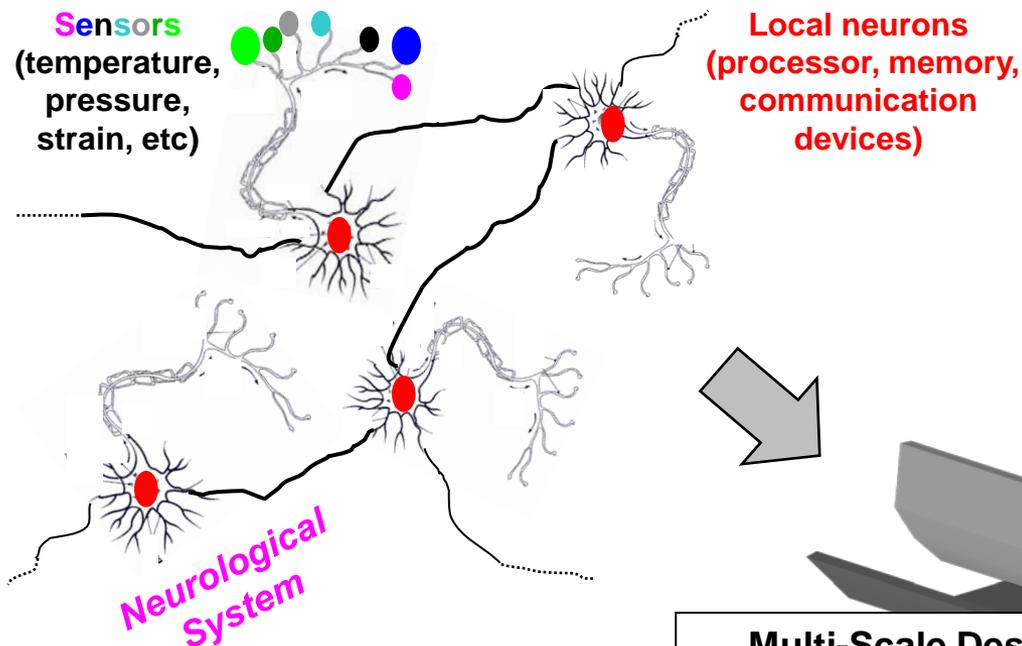
Bondline Integrity:

Depends on the nanotube length (L_c) relative to the bond thickness (H)



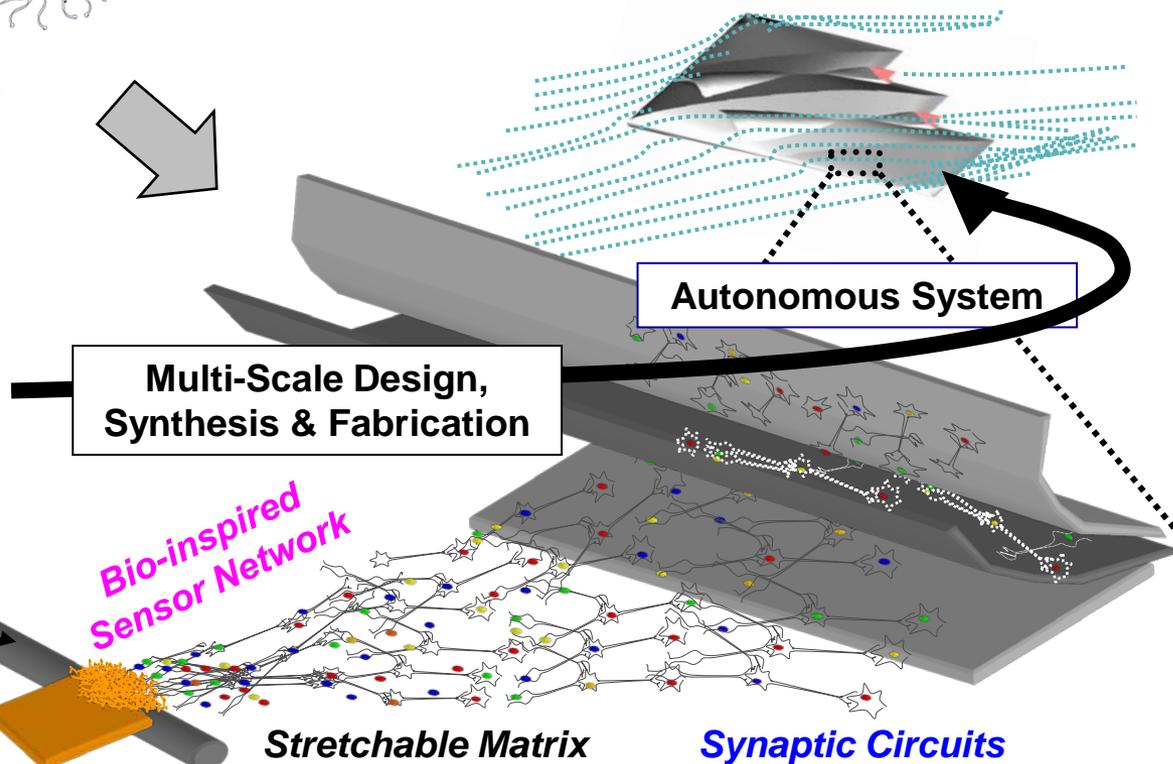
BUILT-IN SENSING NETWORK

(Stanford/UC/DU/UCLA: Chang et al)



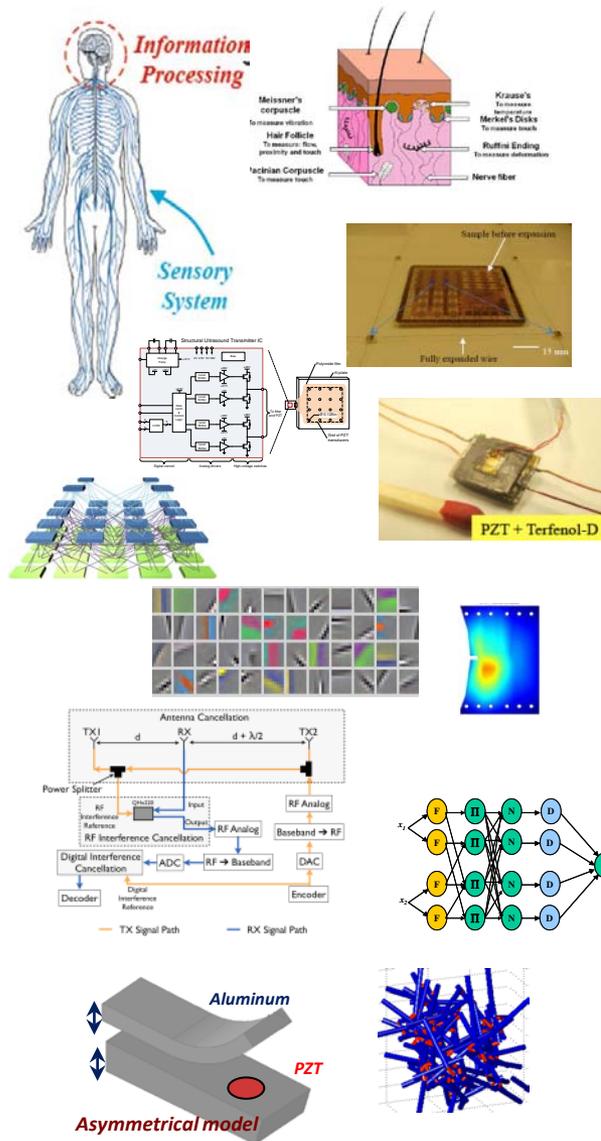
Synapse:
Cognition and decision-making are determined by a relative level of cumulative signal strength with respect to the synapse threshold values

Biological sensory systems rely on **large numbers of sensors** distributed over **large areas** and are specialized to detect and process **a large number of stimuli**. These systems are also capable to **self-organize** and are **damage tolerant**.



BUILT-IN SENSING NETWORK

(Stanford/UC/DU/UCLA: Chang et al)



Objectives:

- Develop a new **multi-scale, multi-physics design and fabrication methodology** that will construct the **bio-inspired sensor system** in **nano/micro scales** but allow the **network** to apply to structures in a **macro scale** to create **self-sensing materials**

Major Tasks and Achievements:

❖ Bio-inspired sensory network

Functionalizing “stretchable” network and characterizing expandability; Rapid fabrication of optical sensor meshes with “flexible” substrate;

❖ Design of Sensors

Screen-printing *PZT* sensors onto network; Design of *airflow* sensors; Fabrication of electromagnetic *nanofiber* composites; Development of sensitive *magnetometer*; Design of new hybrid *optical* sensor;

❖ Embeddable Circuits and Electronics

Densely integrated “interface” circuit for ultrasonic detection of structural defects defects; “Synaptic” circuit with an array of synaptic transistors;

❖ Diagnostics, Recognition and State Awareness

Signal processing and data interpretation for life prediction; Highly scalable feature-learning system identifying factors with greatest impact on performance; Full duplex, single channel wireless system; Neuro-Symbolic-Information-Processing architecture for information extraction, diagnostics, state awareness, and decision-making;

❖ Modeling and Simulation

Development of the method for sensor network optimization to run simulations for different configurations; Modeling of the tunneling effects on the material properties of nanofiber mat for intelligent sensing



SENSORS/ACTUATORS FOR MAV (RW: Abate; RB: Reich; RX: Baur)



CNT-Based Artificial Hair Airflow Sensor

STATE OF THE ART

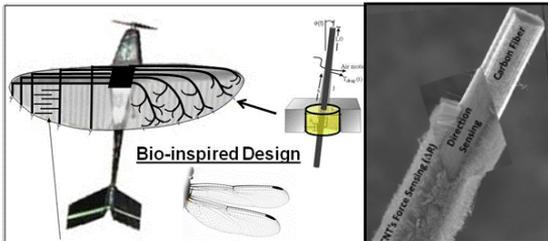
Flow Sensing Hairs - Principles of bio hairs understood, but translation to engineered system with similar performance is not

Models - Models for hair feedback control have not been examined

Materials - Silicon or polymer hairs with optical, piezoresistive, or capacitive transduction shown • Carbon nanotube (CNT) gauge factor to 1000 for single-CNT devices, ~2 for traditional gauge factors, limited work on CNT array strain sensing, even less on fiber

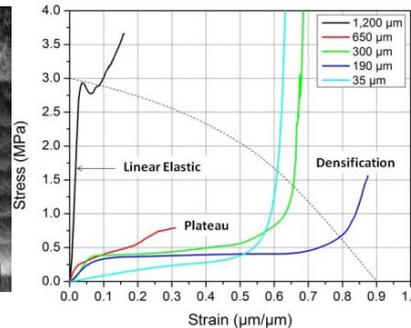
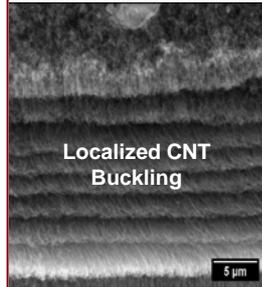
NEW INSIGHTS

- **Artificial Hair Concept** - CNT arrays on rigid fibers have the required hair rigidity/ dimension, displacement sensitivity, material robustness, and design flexibility to enable **integrated flow sensing** to detect gust alleviation and enable complex maneuvering
- **Model** - Hair length vs. boundary layer thickness can be optimized for increased sensitivity
- **Materials** - CNT array mechanics are highly dependent on morphology, but **vertically aligned CNT (VACNT) sensor** yields nearly linear resistance change with strain



Schematic of proposed CNT-coated carbon fiber sensor

MAIN ACHIEVEMENTS:



Nanoindentation of foam-like and beam-like VACNT arrays

Artificial Hair Model - Developed viscoelastic, nonlinear fluid reaction hair sensor model • Explored design geometry & material for individual hair performance

Materials - Characterized morphology effect of VACNT array mechanics • Developed and characterized "first" VACNT-based electromechanical flow/strain sensor

HOW IT WORKS:

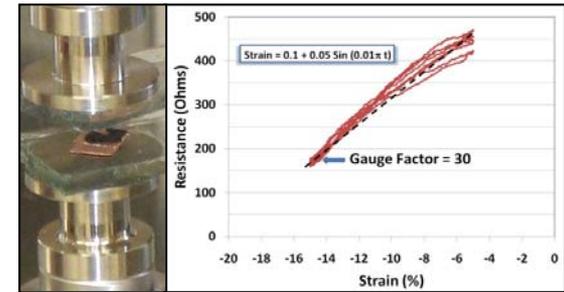
- **Model** - Numerically solve hair sensor governing equations to explore and optimize design
- **Materials** - Compression reorients CNTs, reducing electrical resistance • Force imparted to hair converted to electrical signal within sensor "pore"

ASSUMPTIONS AND LIMITATIONS:

- **Model** - Assume 1-way interaction (flow to hair) with parallel surface, small deflections, rt circular X-section
- **Materials** - Repeatable and uniform CNT deposition • Robust adhesion of CNTs to carbon fiber with environmental changes

Current Impact

- **Optimal hair lengths** are 50-100% of (d_{99}) boundary layer thickness for steady flow
- **Pore sensitive to depth, not width** with 1.5-3 micron level deflections expected
- Planar VACNT sensor gauge factor of 30
- Planar flow sensor created on copper substrate (difficult)



Planar CNT Flow Sensor Prototype on DMA

Planned Impact

- Test CNT sensor in wind tunnel (Eglin AFB)
- Enhance sensor gauge factor
- Extend to fuzzy fiber for artificial hair
- Extend model to oscillatory flow
- Eval. sensor impact on vehicle performance

Research Goals

- Model & validate artificial hair model
- Understand parameter space for optimal sensor performance
- Understand and model physics of electromechanical response of CNT array
- Demonstrate flow sensing capability inside wind tunnel

QUANTITATIVE IMPACT

END-OF-PHASE GOAL



STTR'05: LOAD BEARING ANTENNA FOR SMALL UAV (Geneva/Judd)



Goals

- Develop efficient antennas in **low-frequency** range for small UAV's through structural integration and RF skin excitation
 - *Omni-directional; 30 to 400 MHz (antennas are available in the range from 400 MHz to 3 GHz)*

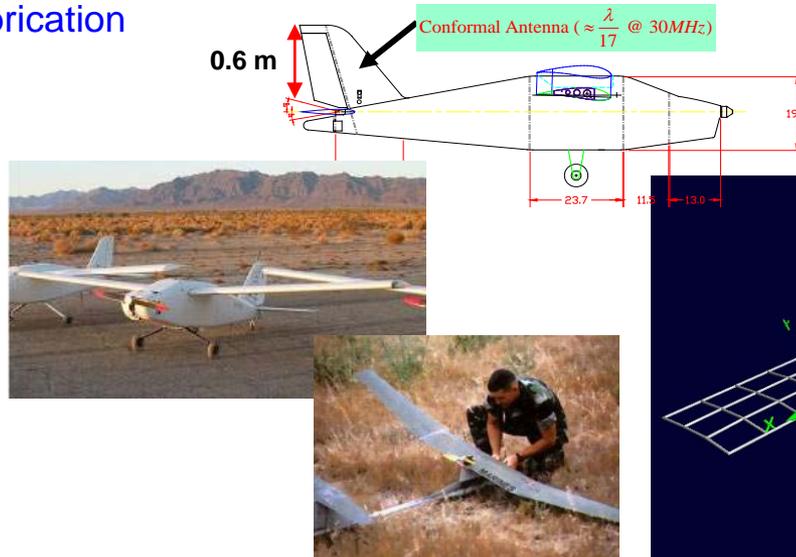
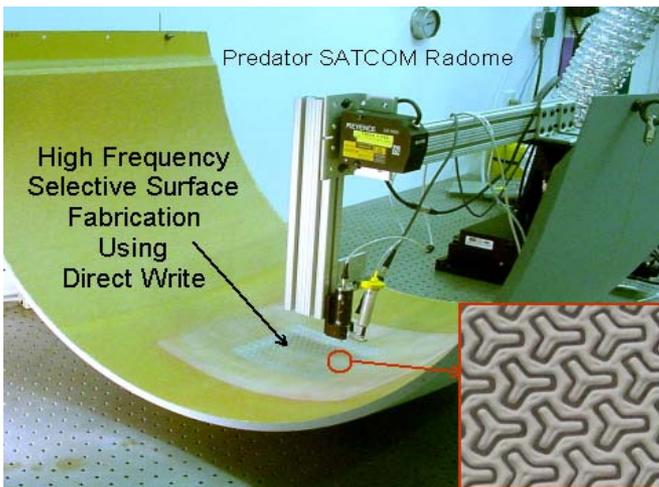
Accomplishments

- Designed spiral antenna with novel feeding scheme. Antenna is conformal to tail of Dakota UAV.
- Designed ground plane conformal to fuselage of Dakota UAV

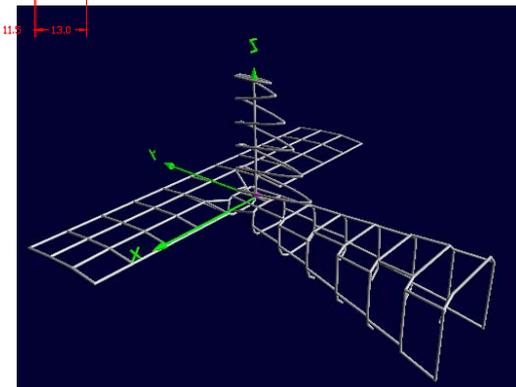
Benefits

- Ability to install **larger apertures**, which is critical at lower frequencies
- New approach where the structure of the aircraft is used more efficiently to install antennas.
- Fundamental design rules for low frequency aperture integration while considering the structure and electrical performance simultaneously.
- **Large bandwidth** antennas can replace several narrow band antenna systems.
- Less aerodynamic drag due to the antennas conformal to the host structure.

SI2 Direct Write Process for Antenna Fabrication



**Spearheaded
6.2 research
at VS & SN**





Game Changer '07: MULTIFUNCTIONAL HYBRID COMPOSITES



PM: B. L. Lee; Co-PM: Arje Nachman

Evaluation: 28 White Papers; 4 Full Proposals

Awarded: Ohio State U, U Minn, UCLA & U Mich

(PI: John Volakis; 3-year grant; 1.1M/yr)

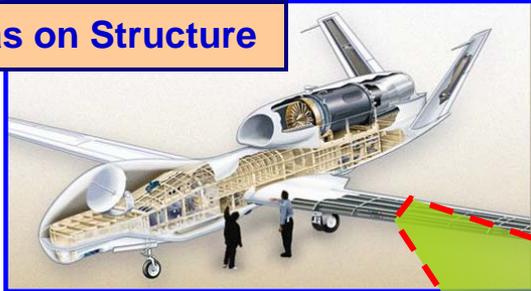
Kick-Off: 4 September 2007, Columbus, OH

Goal

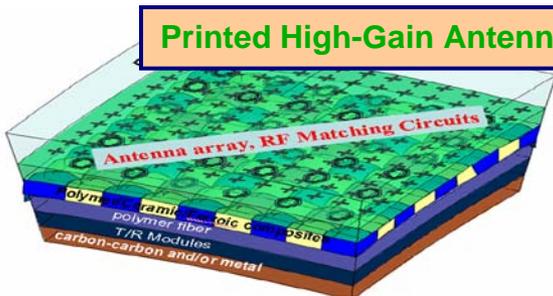
Structurally Integration of Antenna Function through:

- **Materials by Design**
- **N-Reinforcement**
- **Engineered Topography**

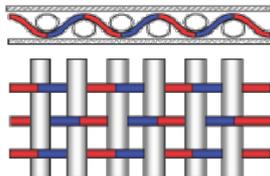
Antennas on Structure



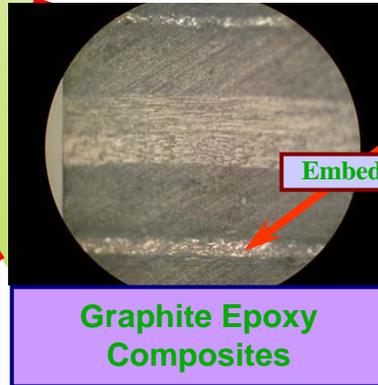
Printed High-Gain Antennas



Textile Conductor



Phased Array Antenna



Graphite Epoxy Composites

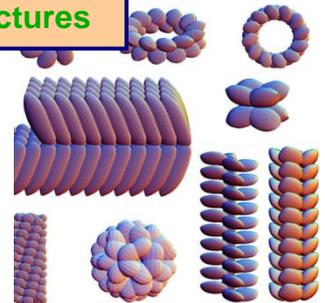
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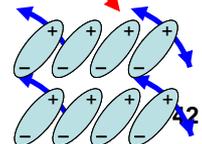
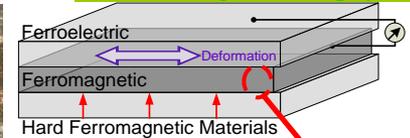
Ferromagnetic materials

Layered Magnetolectric Composites

Low Loss Nanostructures

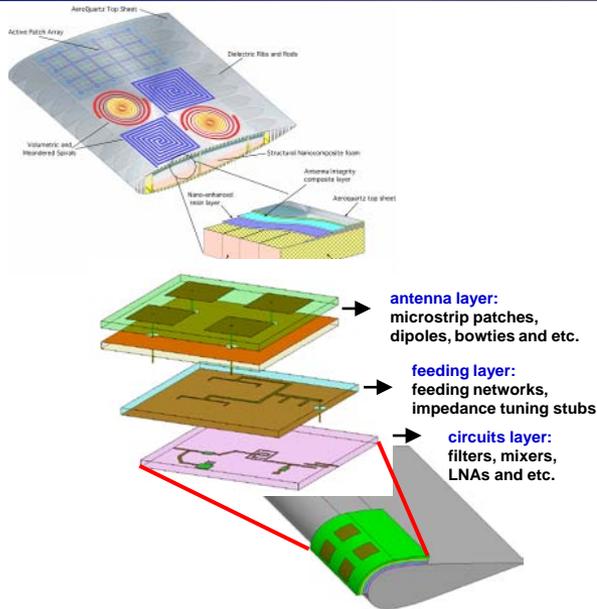


New Design Philosophy





LOAD-BEARING ANTENNAS (OSU/U Mich/U MN/UCLA: Volakis)

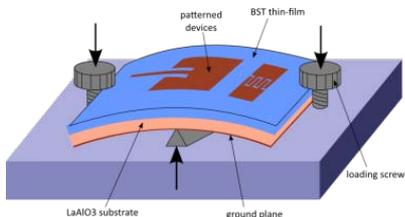
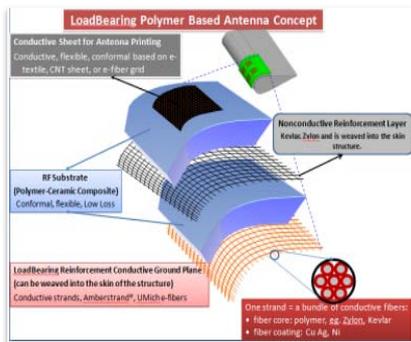


Objectives:

- Design next generation **antennas (broadband and narrowband)** that are **structurally ruggedized, reconfigurable** and sufficiently **miniaturized** for UAV applications.
- Develop a **new class of materials** for load-bearing/conformal/light-weight antennas (incl. ferroelectric, ferromagnetic, multi-ferroic, bondable polymer composites, 3D textiles and nanomaterials).
- Develop analytical techniques for **tractable electro-magneto-thermo-mechanical theory** from fully coupled 3-D equations.
- Integrate new antenna designs into a lightweight structure and develop figures of merit (**design rules**) for **structural integration**.

Main Achievements:

- ❖ Developed new technology by **embroidering metal coated electronic fibers (e-fibers)** on polymers for conformal load bearing antennas.
- ❖ Designed and tested **volumetric and planar woven antennas** based on e-fibers and polymer composites
- ❖ Demonstrated the feasibility of **“first ever” CNT antenna** whose gain is equivalent to the perfectly conducting (but rigid) patch antennas.
- ❖ Developed **coupled multi-physics & multi-scale models for electro-magnetic composite materials** undergoing mechanical excitation.
- ❖ Developed **models to tune antenna via ferroelectrics materials** under mechanical and thermal loads
- ❖ Developed fully overlapping Domain Decomposition Technique for Finite Element Modeling of **small features in large media**



GameChanger '07

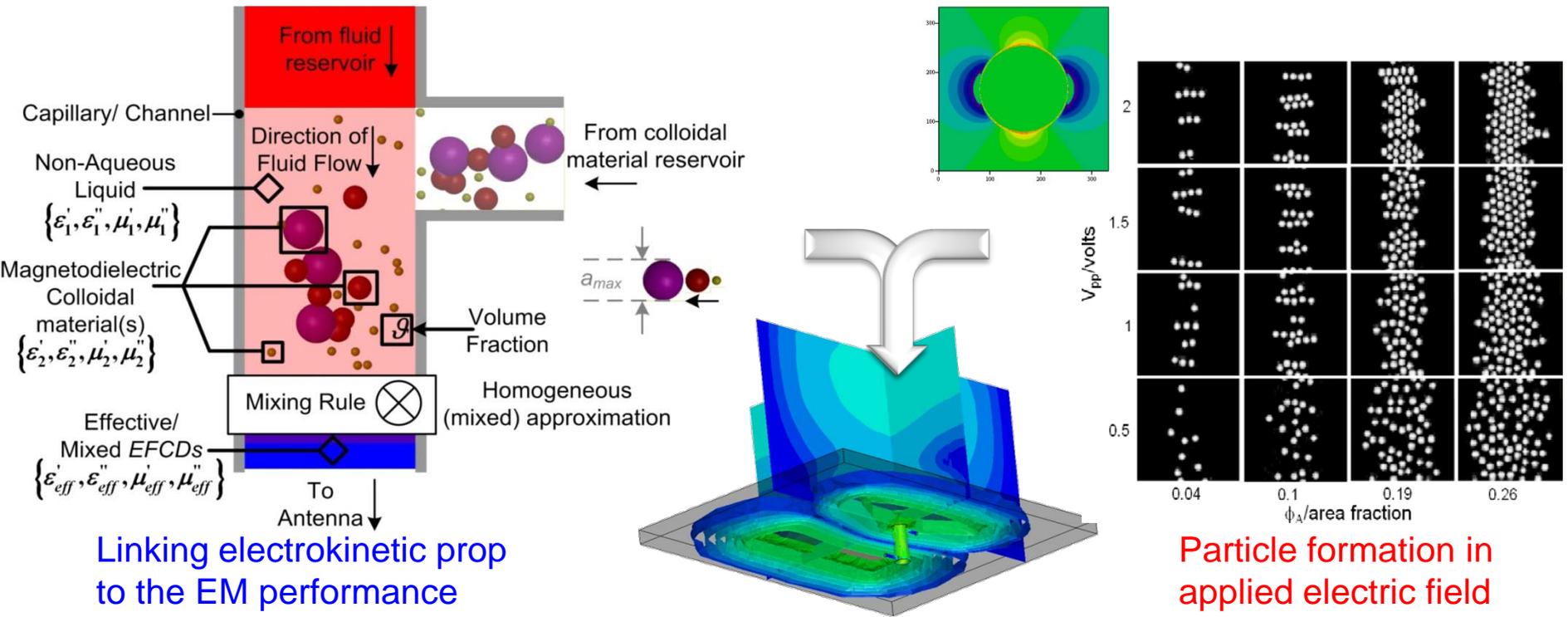
PM: B. L. Lee (NA); Co-PM: Arje Nachman (NE)



ELECTRO-MAGNETICALLY TUNABLE FLUIDS (*TAMU: Huff*)



Goal: Reconfigurable frequency antenna via EM functionalized colloidal dispersions



Linking electrokinetic prop to the EM performance

- Examine the **optimization** of single colloid and concentrated dispersions to achieve desired electromagnetic and microfluidic properties
- Integrate electrokinetic properties using equivalent circuit and analytical **models** to evaluate fundamental RF performance metrics



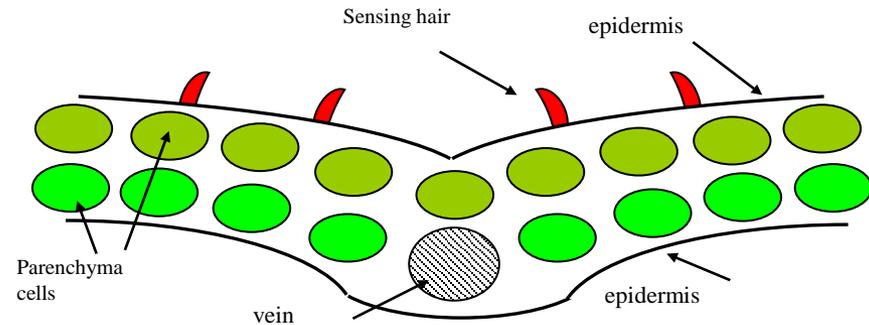
Design by Nature: ADAPTIVE SYSTEM OF FLY TRAP



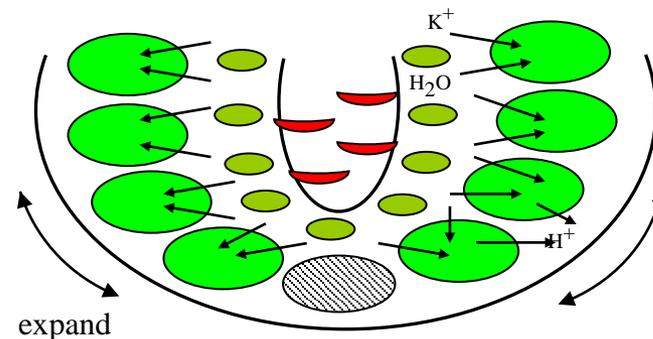
Insect touches the **antenna** located in the middle of leaf



Rapid **closure** of the leaf traps the insect



Cross-section view
BEFORE the leaf motion



AFTER the leaf motion

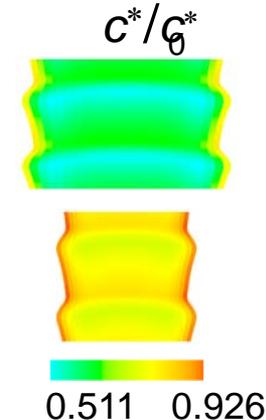
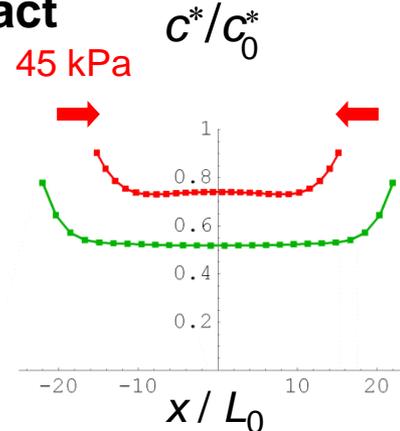
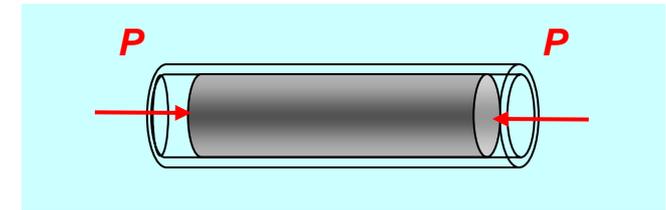
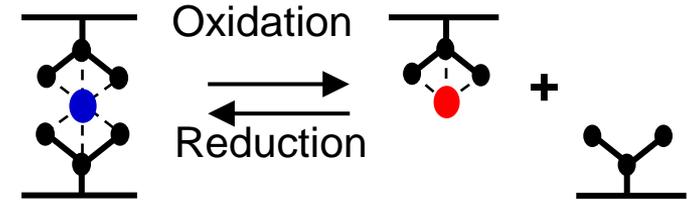
M. Taya (U Washington)



DESIGNING SELF-REINFORCING MATERIALS (*U Pitt: Balazs*)



- Developed model to describe BZ gels with chemo-responsive X-links
 - Modified Oregonator model
 - f – dependent complex formation
 - Time-dependent elastic contribution
- Studied response to steady and periodic compression in 1D model
- Mechanical impact increases X-link density
 - Self-reinforcing material
 - Stiffens in response to impact



V.V. Yashin, O. Kuksenok, A.C. Balazs,
J. Phys. Chem. B 2010, **114**(19), 6316.



VISION: *EXPANDED*



Acknowledgement:

Scott White (UIUC)
Jeffrey Moore (UIUC)
Nancy Sottos (UIUC)
Sia Nemat-Nasser (UC San Diego)
Markus Buehler (MIT)
Scott White (UIUC)*
*Jeffrey Moore (UIUC)**
*Nancy Sottos (UIUC)**
*Jennifer Lewis (UIUC)**
*Philippe Geubelle (UIUC)**
*Kenneth Christensen (UIUC)**
*Jonathan Freund (UIUC)**
Chris Mangun (CU Aero)
Tom Darlington (Nanocomposix)
Tony Starr (SensorMetrix)
Tom Hahn (UCLA)

* **MURI**

AUTONOMIC AEROSPACE STRUCTURES

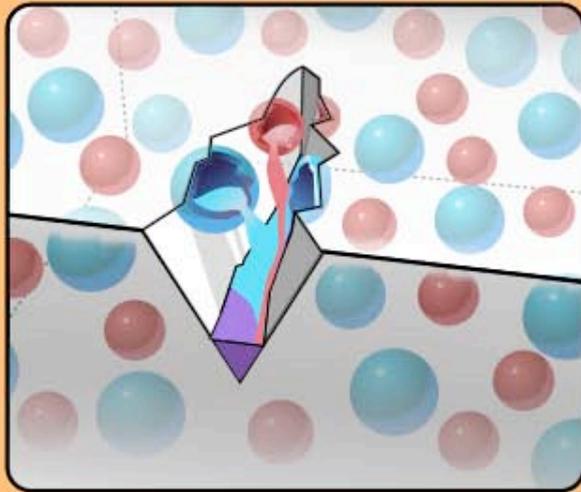
- sensing & Precognition***
- Self-Diagnosis & Actuation***
 - **Self-Healing**
- Threat Neutralization***
 - **Self-Cooling**
 - **Self-Powered**



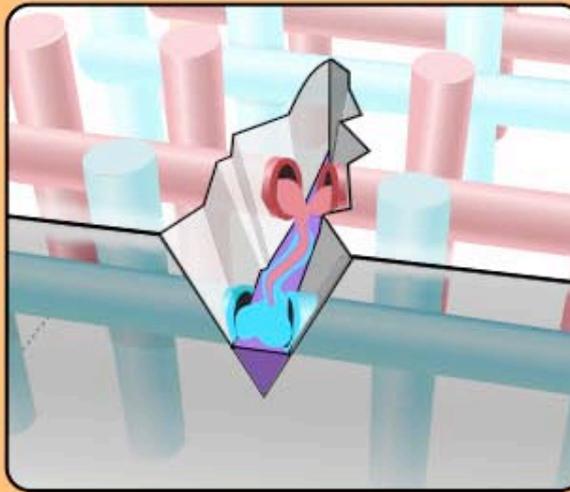
- **site specific**
- **autonomic**



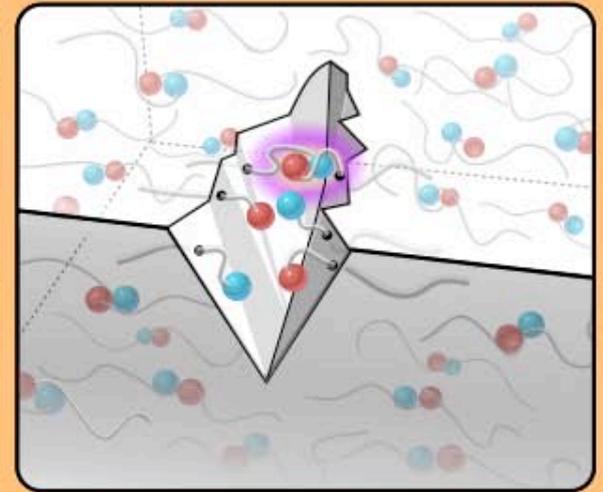
THREE APPROACHES FOR SELF-HEALING



(a) Capsule-based



(b) Vascular

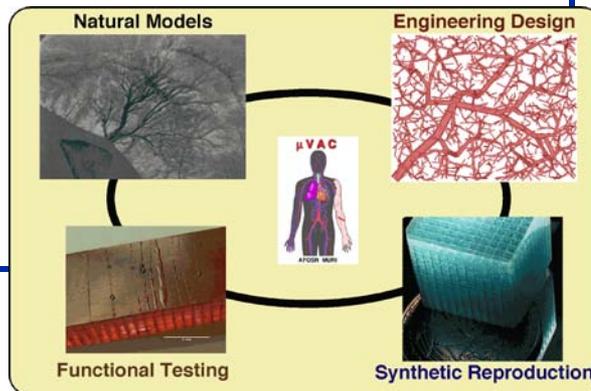
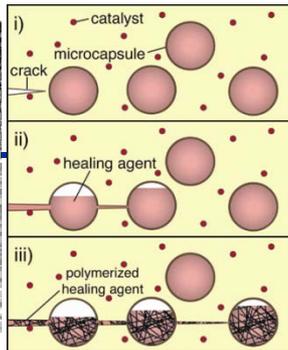


(c) Intrinsic

Objective:

To achieve synthetic reproduction of **autonomic** functions, such as **self-healing** and **self-cooling**, for aerospace platforms through creation and integration of complex materials systems containing **microvascular architectures**.

Nature '01



DoD Benefit:

The advances in self-healing and self-cooling composite structures will lead to the **increase of reliability** and **responsiveness** of aerospace vehicles allowing **longer flight time** and **reduced chance for unexpected failure**.

Technical Approach:

(a) **Natural models** of microvascular systems are studied to guide the engineering design of **optimal networks** for self-healing and self-cooling structural composites. (b) These networks are fabricated using “**direct-write**” assembly techniques while integrating material components that realize the desired **multi-functionality**. (c) A full compliment of experimental and analytical techniques are employed to demonstrate system **efficiency**.

Budget:

	FY05	FY06	FY07	FY08	FY09	FY10
\$K	504,311	1,242,709	1,047,076	1,115,244	1,057,424	500,920

Major Reviews/Meetings:

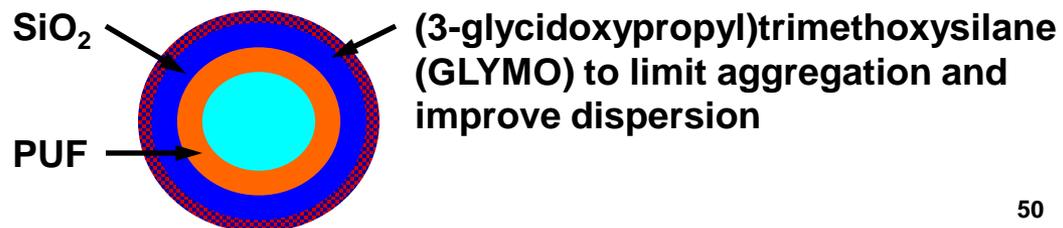
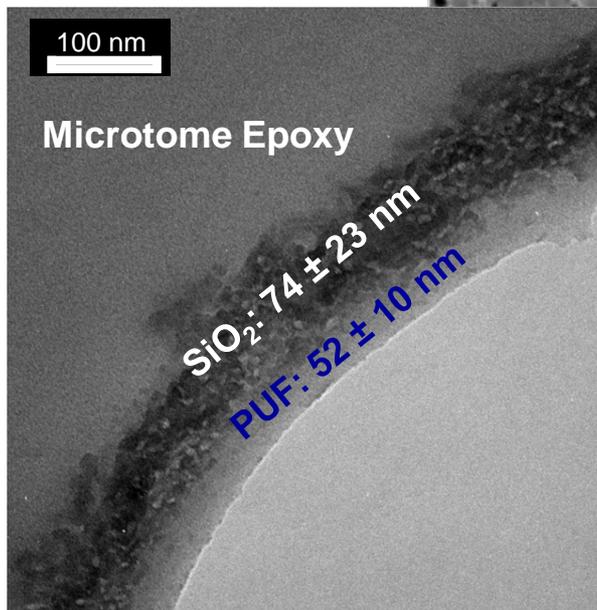
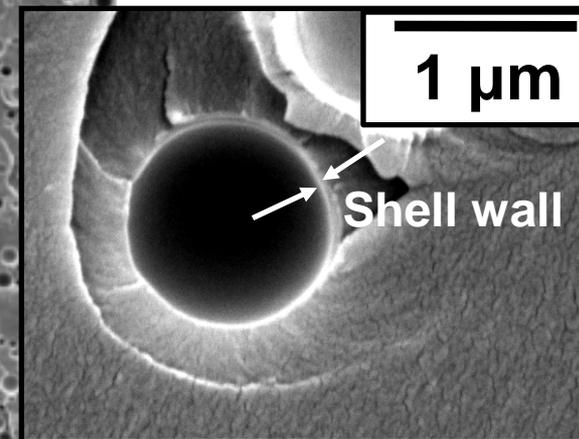
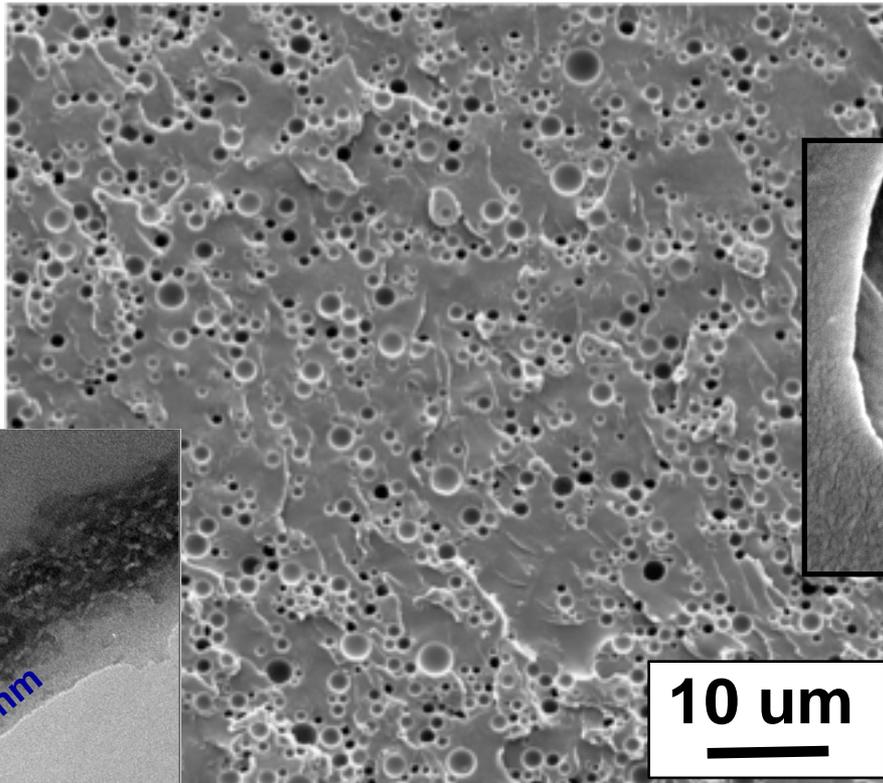
- 30 August 2006: Seattle, WA
- 20 August 2007: Urbana, IL
- 21 August 2008: Arlington, VA
- 31 August 2009: Urbana, IL
- 12 September 2011: Urbana, IL



Core'09: MICRO & NANOCAPSULES FOR SELF-HEALING (UIUC: Sottos)



SEM of 20wt% functionalized capsules in Epoxy (EPON 828/DETA)





MURI Spin-off >> STTR'08: THERMALLY REMENDABLE COMPOSITES



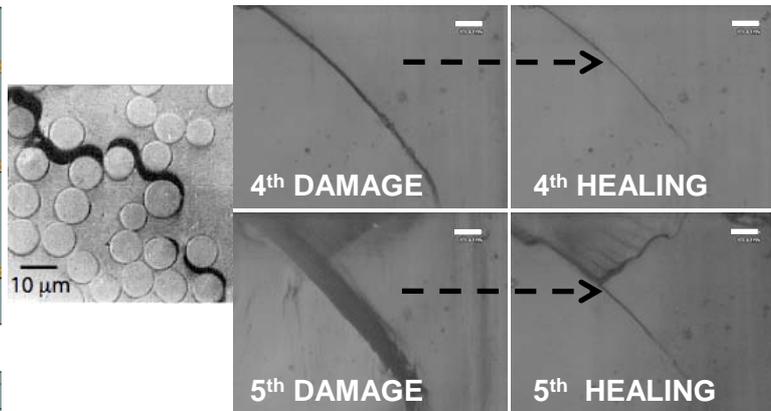
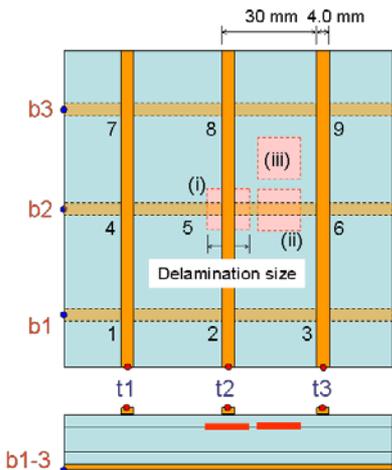
MURI '05 THERMALLY REMENDABLE POLYMERS (UCLA: Wudl)

HEAT

Polymer

19

- Crosslink bonds of Diels-Alder cyclo-addition polymers are **thermally reversible** and can be reestablished after separation (unlike epoxy)
- Fabricated CFRPs with thermally remendable matrix materials and **resistive heating network of carbon fiber reinforcement**
- **Demonstrated multiple rounds of healing** of delamination and microcracks
- Resistive heating is dependent on layup orientation and most uniform with surface electrodes laid at 45° relative to fibers
- Structural properties of CFRPs are comparable to traditional epoxy based CFRPs

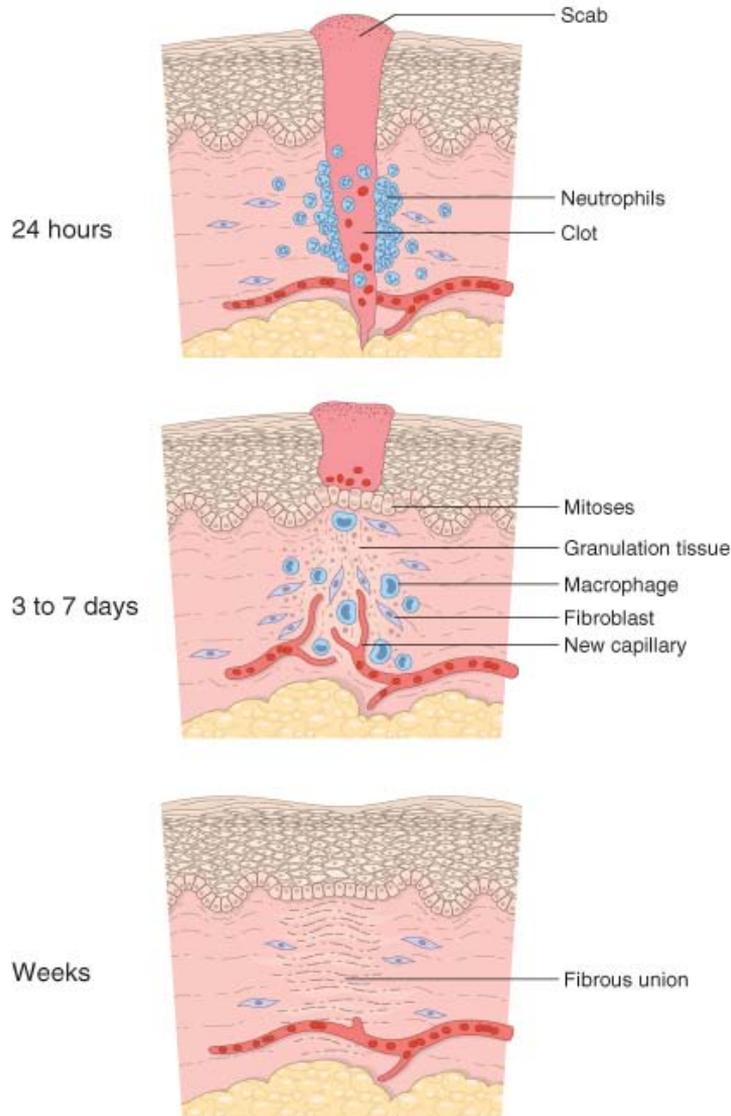


Healing of Delamination	Strain Energy (mJ)	Healing Efficiency (Time)
Virgin	10.04	
1 st healing	8.68	86.4% (1 hr)
2 nd healing	8.88	88.4% (2 hr)
3 rd healing	9.82	97.8% (3 hr)
4 th healing	9.42	93.8% (3 hr)





Design by Nature: HEALING OF SKIN *(Krafts, 2008)*



- **By 24 hours**
 - clot forms
 - white blood cells come in
 - epithelium begins to regenerate
- **By 3-7 days**
 - macrophages come in
 - granulation tissue is formed
 - new blood vessels
 - fibroblasts
 - collagen begins to bridge incision
 - epithelium increases in thickness
- **Weeks later**
 - granulation tissue gone
 - collagen is remodeled
 - epidermis full, mature
 - eventually, scar forms



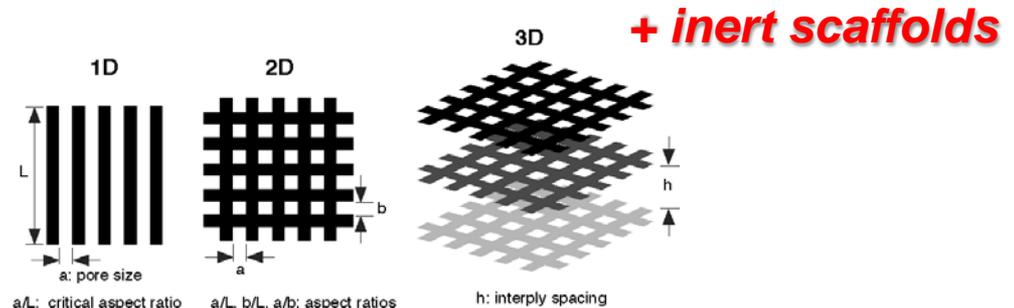
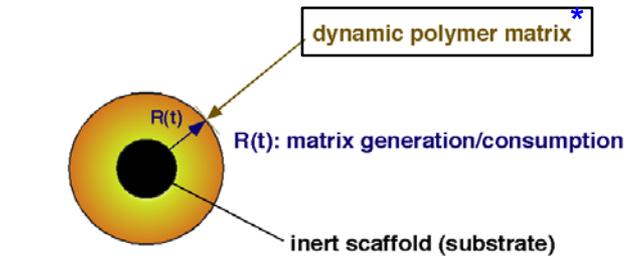
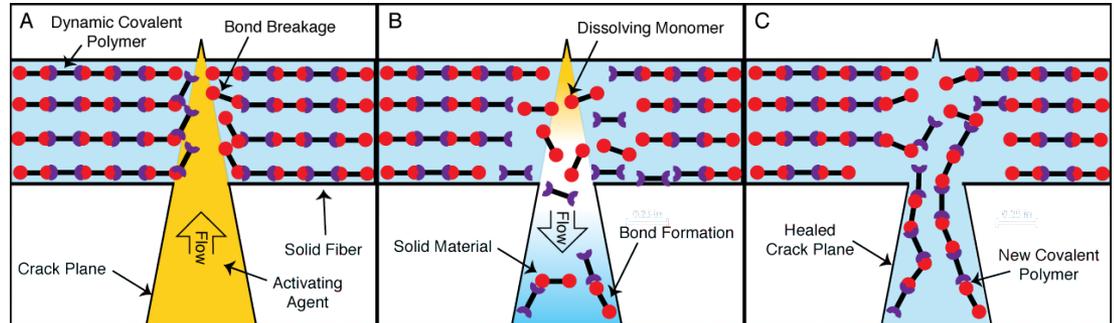
Core'10: BIO-INSPIRED STRUCTURAL REMODELING (UIUC: White/Moore)



Regeneration in biology:

Invertebrates	 Cnidarians and sponges [e.g. corals, jellyfish]	
	 Echinoderms [e.g. starfish]	 Planarians [e.g. flatworms]
Vertebrates	 Salamanders	 Humans

New approach: *Dynamic polymers*



* *Dynamic polymers can be reversibly changed from liquid to solid and vice versa due to dynamic covalent bond that can be triggered to disassociate by an activating agent.*



VISION: *EXPANDED*



Acknowledgement:

Abraham Stroock (Cornell U)
Noel Holbrook (Harvard U)
Patrick Kwon (Mich St U)
Vikas Prakash (Case Western)
Scott White (UIUC)*
*Jeffrey Moore (UIUC)**
*Nancy Sottos (UIUC)**
*Jennifer Lewis (UIUC)**
*Philippe Geubelle (UIUC)**
*Kenneth Christensen (UIUC)**
*Jonathan Freund (UIUC)**
Ajit Roy (AFRL/RXBT)
Jeff Baur (AFRL/RXBC)

* MURI

d

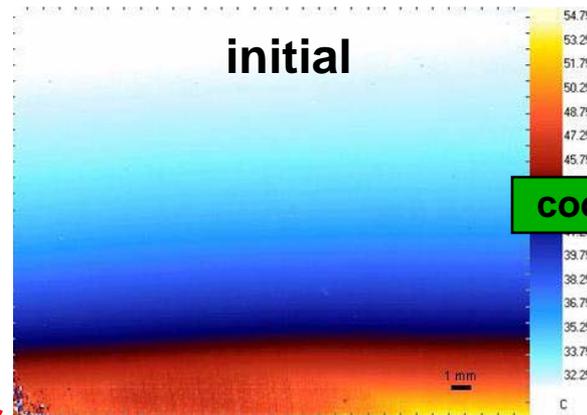
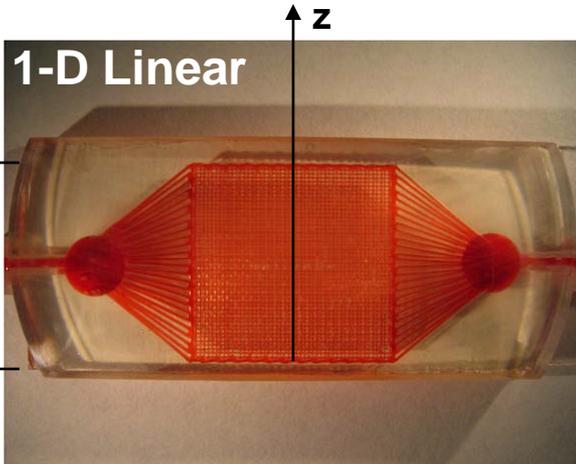
AUTONOMIC AEROSPACE STRUCTURES

Sensing & Precognition
Self-Diagnosis & Actuation

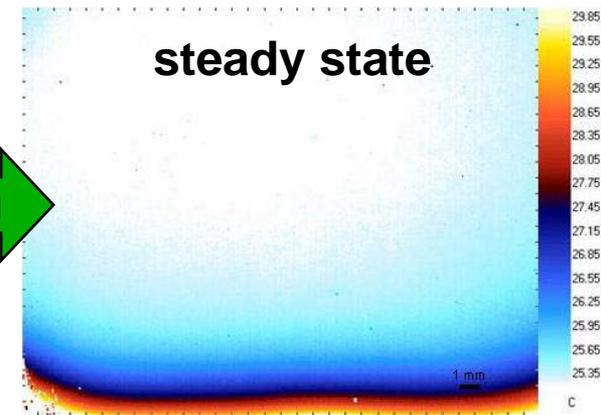
- Self-Healing
- Threat Neutralization
- Self-Cooling
- *Self-Powered*



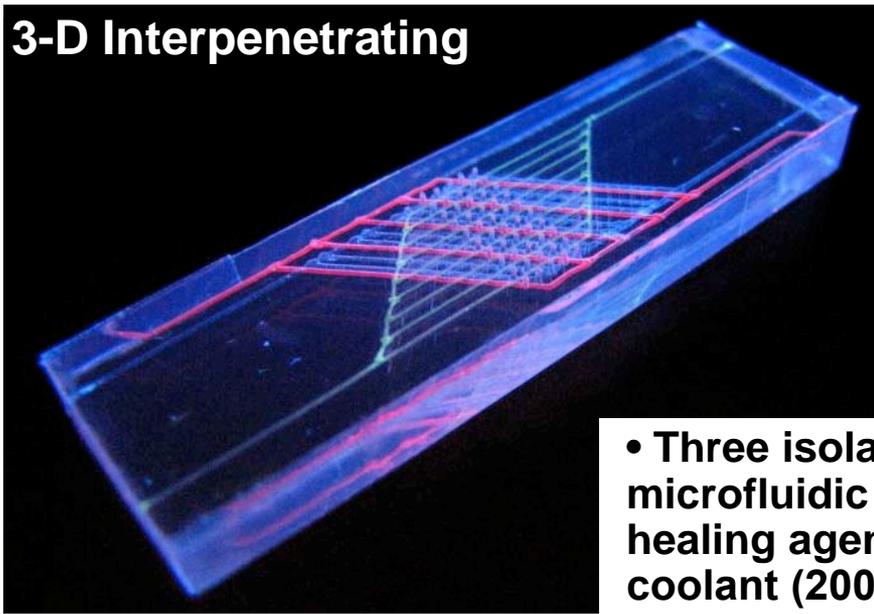
- site specific
- autonomic



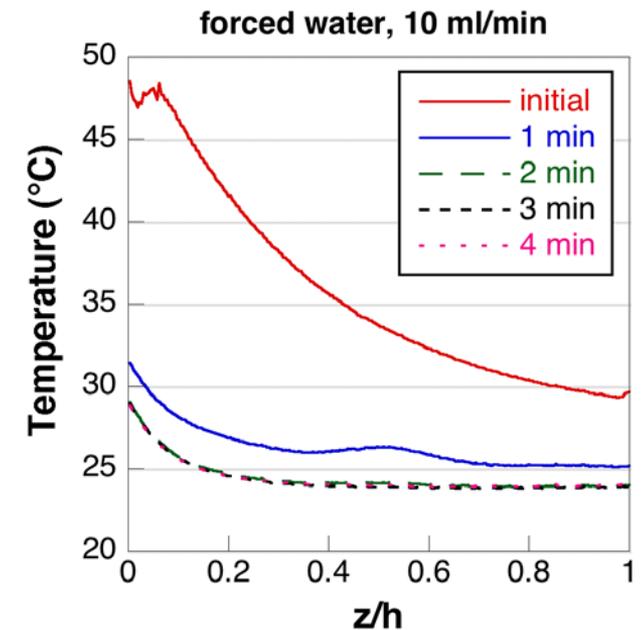
cooling



3-D Interpenetrating



- Three isolated microfluidic networks for healing agents and coolant (200 μ diam)





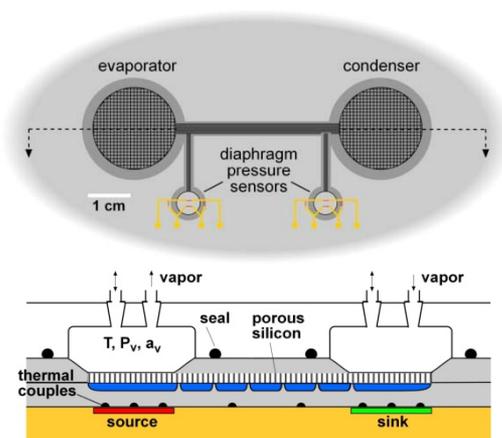
PLANT-MIMETIC HEAT PIPES (Cornell U / Harvard U: Stroock)



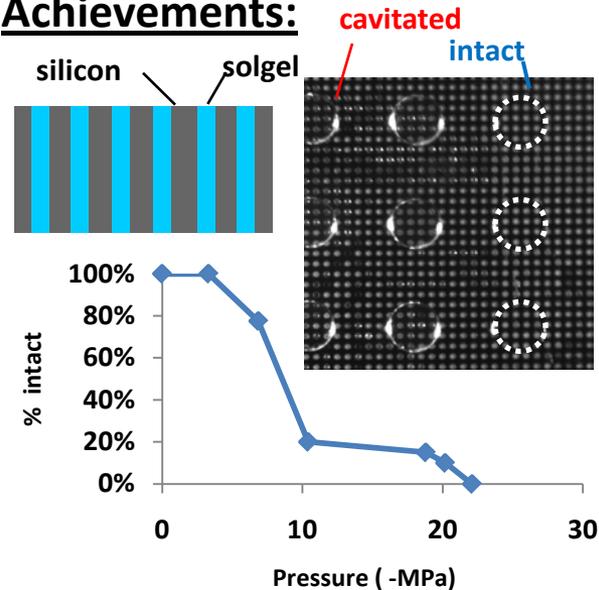
Objectives:

- Robust **heat transfer** in the presence of large **gravitational** and **inertial stresses**.
- **Plant mimetic** use of liquids at large negative pressures within a **microfluidic heat pipe**.
- Fundamental understanding of **thermodynamics** and **transport processes** in this regime.
- Insights into plant strategies for the management of **negative pressures** and **recovery from cavitation**.

MEMS platform

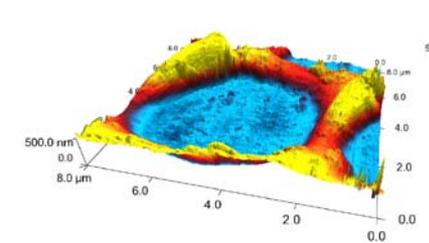


Achievements:



Fabrication

- Development of **wick membrane in silicon platform** with unprecedented stability (down to -200 bars - Figure).
- Development of **MEMS sensor** for measuring **pressures down to -500 bars**.
- Figure: Development and testing of inorganic wick membrane. Stability limit of liquid water. Complete stability to -3 MPa (-30 bars). Absolute limit: -20 MPa (-200 bars).



Plant physiology

- Elucidation of structure and biochemistry of **xylem vessel** elements implicated in **autonomic refilling**.
- Physical, chemical, and biological characterization
- Figure: AFM image of bordered pit membrane.



Perspectives:

- Foundation of technical approaches and physical and biological understanding to enable **robust engineering with liquids at negative pressures**.
- Efficient, passive heat transfer with small form factor and weight for **avionics cooling**.



VISION: *EXPANDED*



Acknowledgement:

Max Shtein (U Mich)
Henry Sodano (U FL)
Dan Inman (VA Tech)
Sven Bilén (Penn St U)
Michael Strano (MIT)
Greg Carman (UCLA)
Gleb Yushin (GA Tech)
Minoru Taya (U WA)*
Paolo Feraboli (U WA)*
Martin Dunn (U CO)*
Ronggui Yang (U CO)*
Kurt Maute (U CO)*
Se-Hee Lee (U CO)*
Y. Sungtaek Ju (UCLA)*
Tom Hahn (UCLA)*
Dan Inman (VA Tech)*
Ioannis Chasiotis (UIUC)*
Carl Schulenburg (PowerMEMS)
Tim Fisher (Purdue U)
Benji Maruyama (AFRL/RXBN)
Thuy Dang (AFRL/RXBN)
Michael Durstock (AFRL/RXBN)

* MURI

AUTONOMIC AEROSPACE STRUCTURES

Sensing & Precognition

Self-Diagnosis & Actuation

- **Self-Healing**

Threat Neutralization

- **Self-Cooling**

- **Self-Powered**

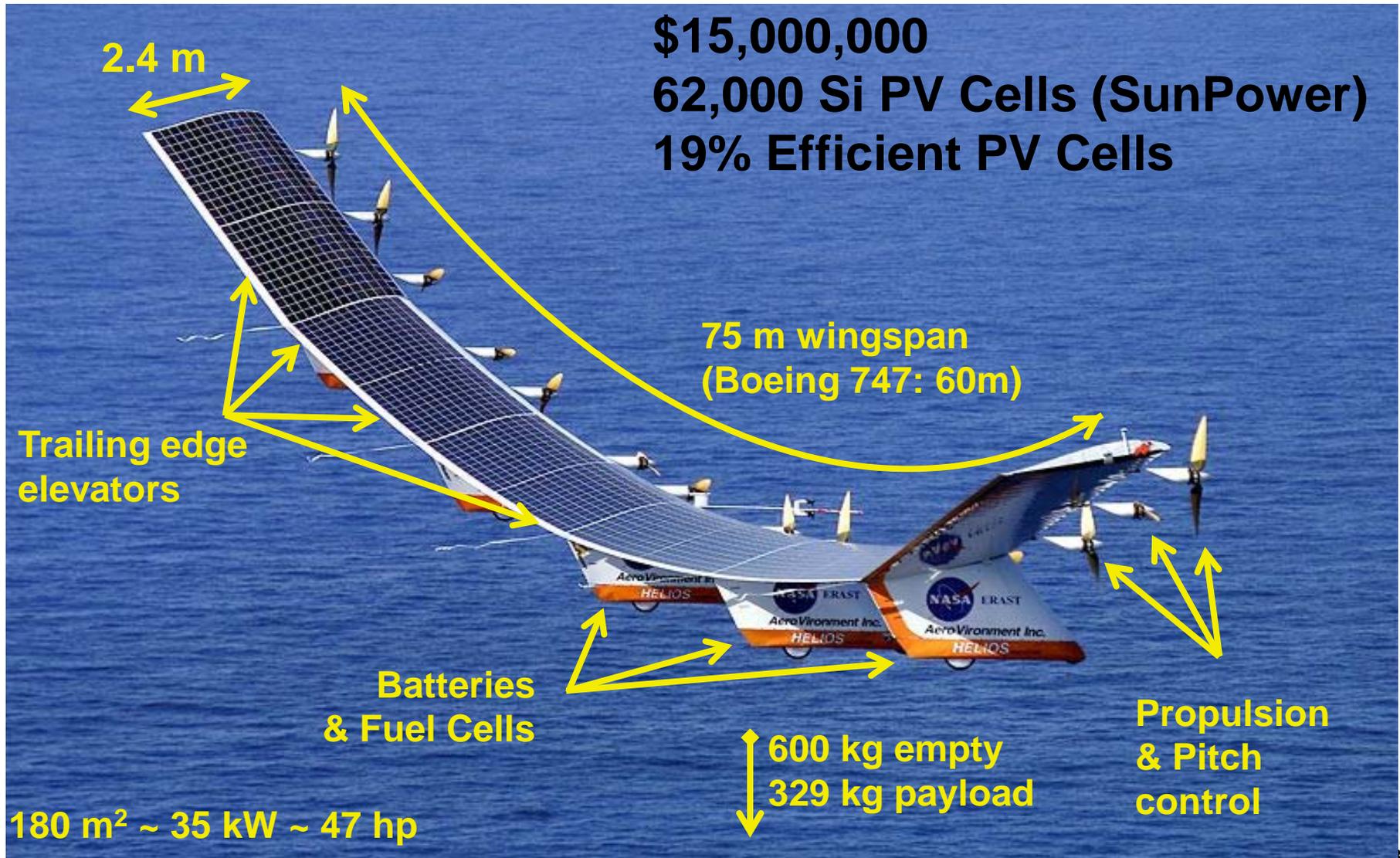


- **site specific**
- **autonomic**

***Energy from
Aerospace
Environ***



NASA "HELIOS"

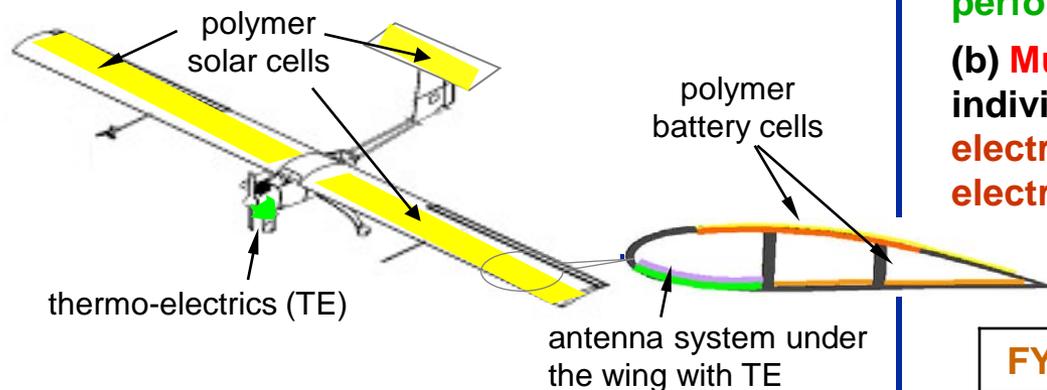


INTEGR'D ENERGY HARVESTING (U WA/U CO/UCLA/VPI: Taya et al)



Objective:

To develop “self-powered” load-bearing structures with **integrated energy harvest/storage capabilities**, and to establish new **multi-functional design rules** for structural integration of energy conversion means.



DoD Benefit:

Self-powered load-bearing structures with integrated energy harvest/storage capabilities will provide meaningful **mass savings** and **reduced external power requirements** over a wide range of defense platforms including **space vehicles**, **manned aircraft**, **unmanned aerial vehicles**, and **ISR systems**.

Technical Approach:

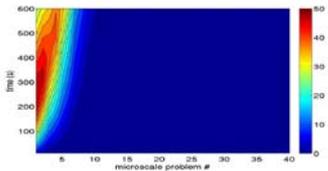
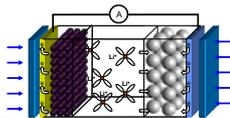
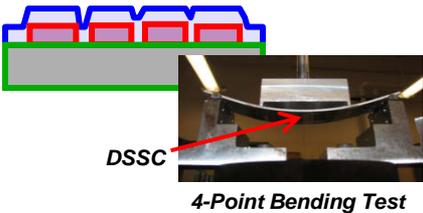
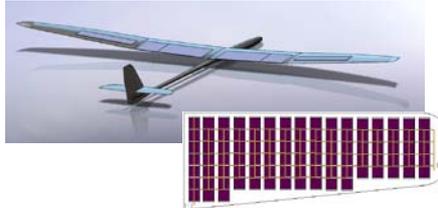
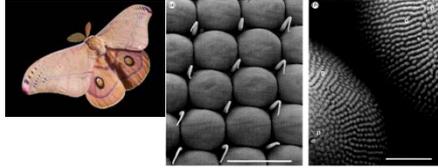
- (a) A combination of experimental and analytical techniques are employed to advance the **efficiency** of the energy conversion means (as an integral part of **load-bearing** structures) and to optimize their multifunctional **performance** and **ability to cover larger areas**.
- (b) **Multifunctional composites** are created with individual layers acting as **photovoltaic/thermo-electric/piezoelectric** power harvesting and **electrochemical** power storage elements.

Budget:

	FY06	FY07	FY08	FY09	FY10	FY11
\$K	693,335	1,169,560	1,180,608	1,219,324	1,179,991	568,571

Major Reviews/Meetings:

- 29 August 2007: Seattle, WA
- 5 August 2008: Boulder, CO
- 11 August 2009: Blacksburg, VA
- 18 August 2010: Los Angeles, CA
- 5 August 2011: Arlington, VA



Year 4 Highlights

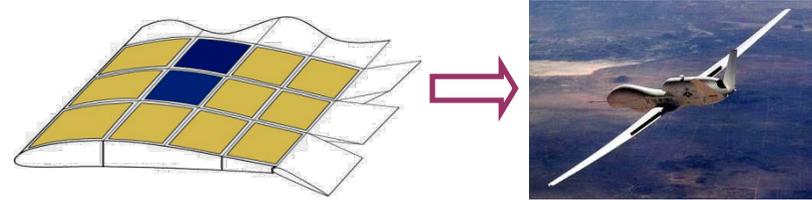
- Developed new “anti-reflection” surface coating inspired by **moth eyes** for solar cells with higher transmittance
- Process **scale-up of dye-sensitized solar cells (DSSC)**
- Integrated the DSSC onto a quasi-wing structure and confirmed the **endurance under 44,000+ bending cycles**
- “Shrink-fit integration” and **FGM electrodes for linear TE modules** with increased durability
- **Microwave synthesis** of nano-particles of Bi_2Te_3
- Design of “scalable” and “stretchable” **thin-film Li ion batteries** for UAV structures
- **Modeling of electrochemical and mechanical response of solid-state electrolyte** and their morphology effects
- **Simulations predicting onset of mechanical failure** leading to capacity fade in agreement with experiments
- Experimental characterization of **cracking and twinning in Si anode with Li ion insertion** (*first-ever* observation).
- Assessed **battery survivability in co-curing environment**
- **UAV test bed** at U Colorado



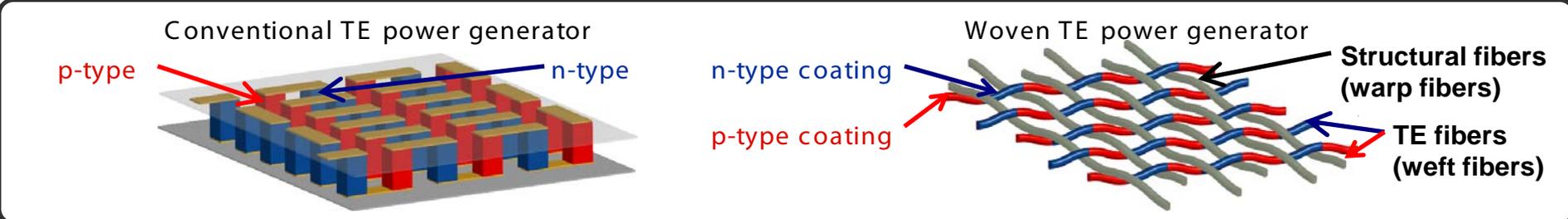
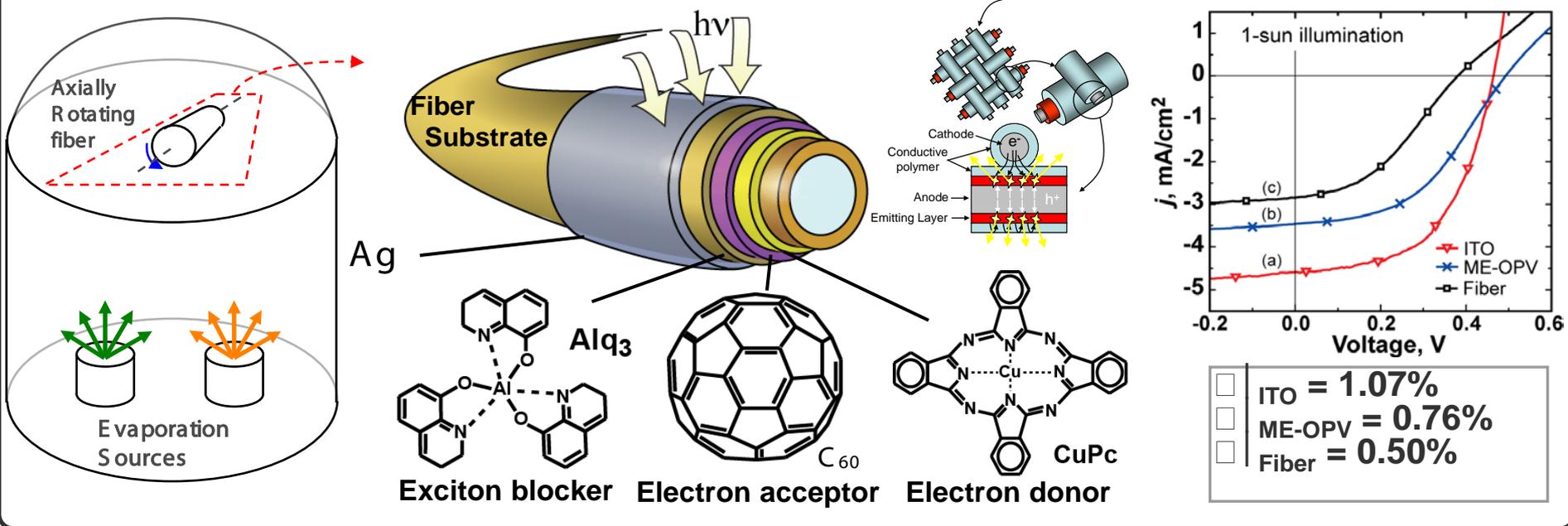
Core / PECASE: ENERGY HARVESTING TEXTILES (U Mich: Shtein)



Objective: Create woven active fabrics to enable light-weight conformable energy generators
(Finalist for MURI'06; Director's Discretionary Fund)



Solar energy harvesting fibers that show high power density, low weight





AGENDA



- Background
- Trends and Issues
- Sensory Networks
- Self-Healing & Self-Cooling
- Self-Powered Systems
- **Future Plans**
- **Summary**



VISION: *EXPANDED*



Biomimetics

**Design for Coupled
Multi-functionality**

Nano-materials

**Multi-scale
Model**

**Micro- & Nano-
Devices**

Manufacturing Sci

**Neural Network &
Information Sci**

AUTONOMIC AEROSPACE STRUCTURES

- *Sensing & Precognition*
- *Self-Diagnosis & Actuation*
 - **Self-Healing**
 - **Threat Neutralization**
 - **Self-Cooling**
 - *Self-Powered*



- **site specific**
- **autonomic**



BIO-INSPIRED SYSTEMS: BEYOND CURRENT VISION



VISION: *EXPANDED*



Scott White (UIUC)

Biomimetics

Design for Coupled
Multi-functionality

Nano-materials

Multi-scale
Model

Micro- & Nano-
Devices

Manufacturing Sci

Neural Network &
Information Sci

**AUTONOMIC
AEROSPACE
STRUCTURES**

- Sensing & Precognition
- Self-Diagnosis & Active Regulation
- Self-Healing
- Threat Neutralization
- Self-Cooling
- Self-Powered

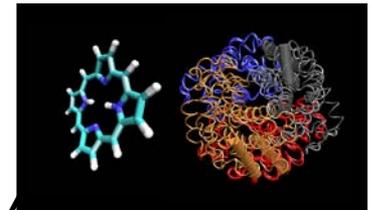
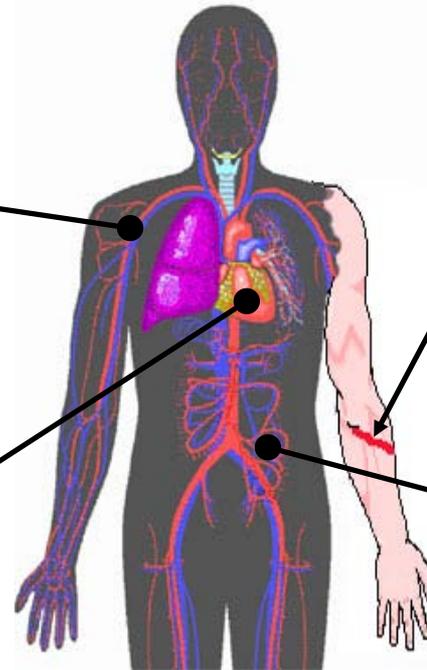
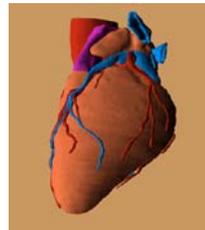


FUNCTIONS OF INTEREST



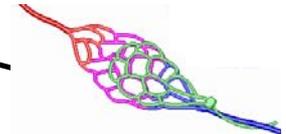
**Self-Regulating
Function**

Active Regulation



**Self-Generating
Function**

Mesoporous Networks

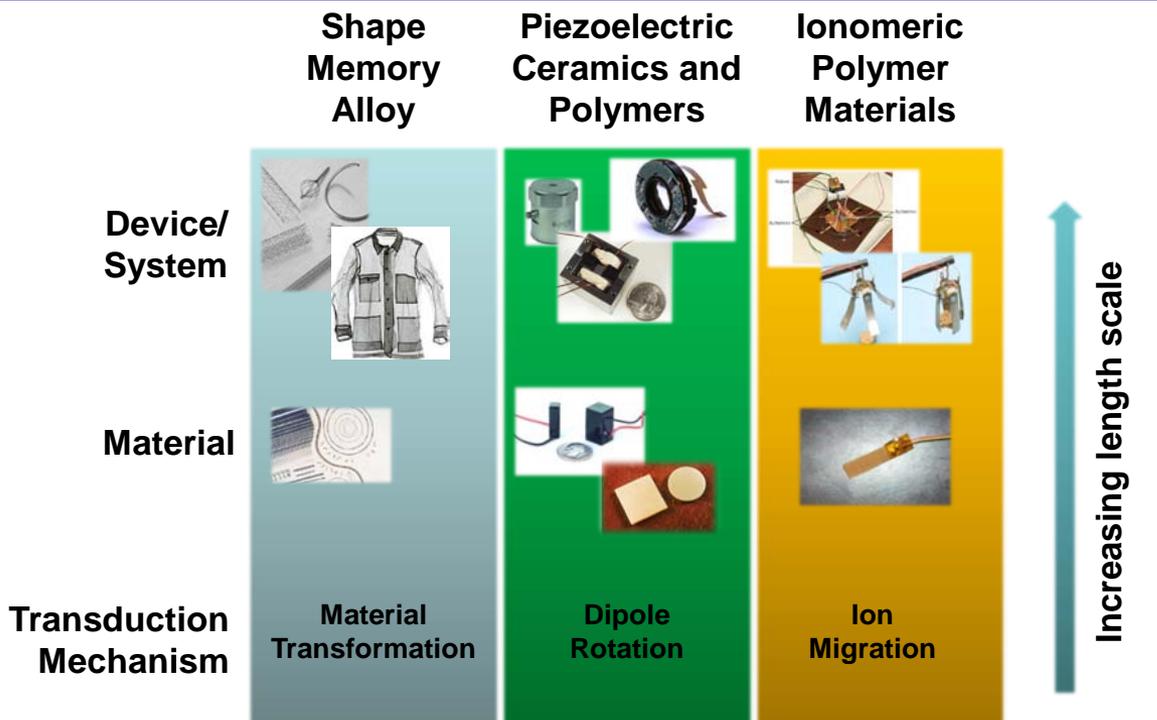




ENGINEERED DEVICES: BEYOND CURRENT VISION



Traditional Transducer Materials



Center for Intelligent Material Systems and Structures
at Virginia Polytechnic Institute and State University

donleo@vt.edu

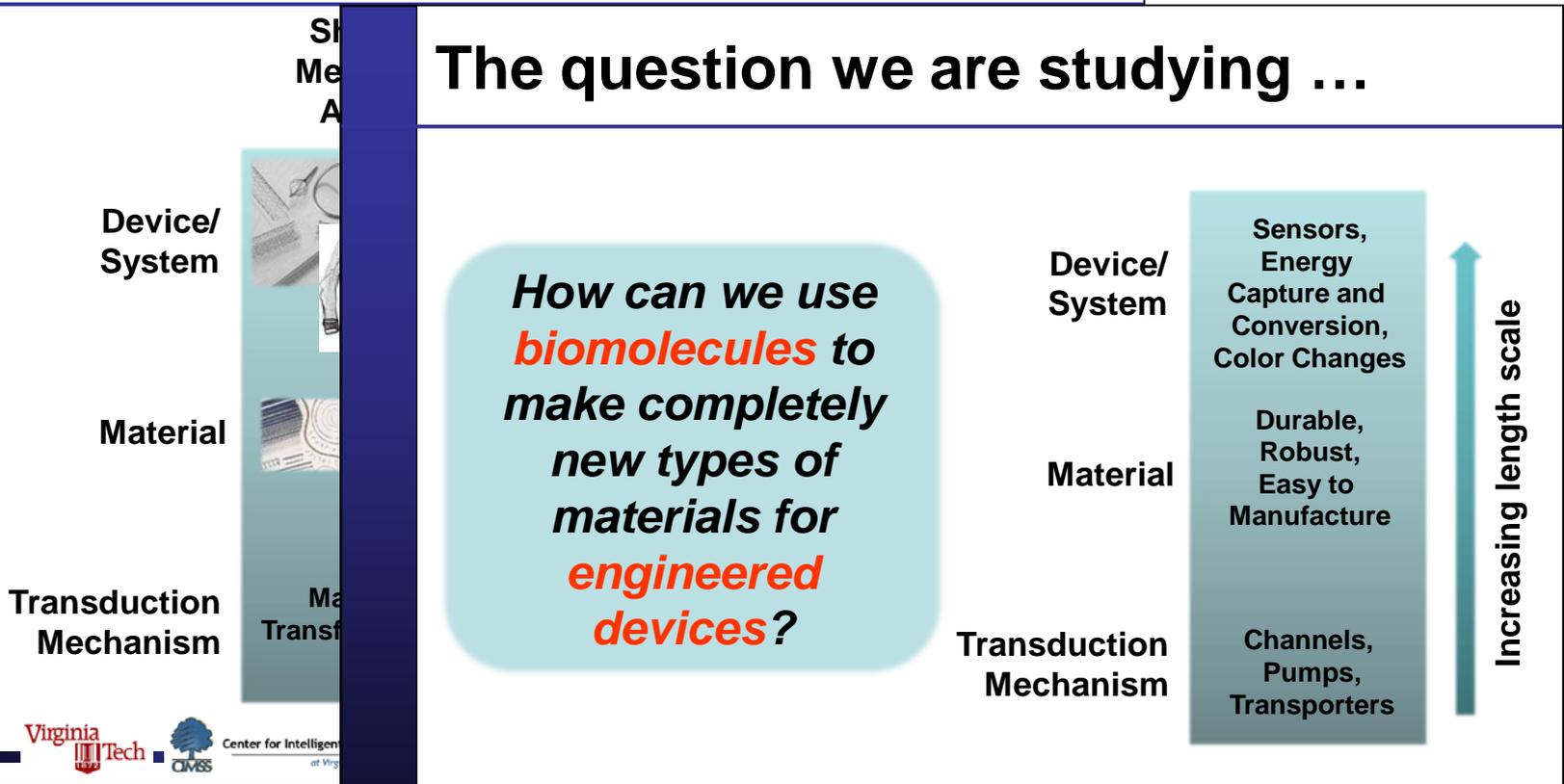
Don Leo (VA Tech)



ENGINEERED DEVICES: BEYOND CURRENT VISION



Traditional Transducer Materials





SUMMARY



- The community is fully committed to the establishment of advanced **multi-functional** aerospace structures.
- A major progress has been made in pursuing a new **vision** for **autonomic systems** and providing research support for baseline multifunctional materials and microsystems.
- Specific initiatives for autonomic aerospace structures are implemented covering the focus areas of: *“self-healing/self-cooling composites,” “structurally integrated energy harvest/storage capabilities,” “load bearing antennas,” “reconfigurable multifunctional structures,”* “energy harvesting from aerospace environment” and *“neurological system inspired sensory network.”*
- New initiatives are planned for *“neutralization of penetration/EM threats,” “multiscale analysis for reliability and multifunctional design”* and the follow-up of the above-described focus areas.