



MECHANICS OF MULTIFUNCTIONAL MATERIALS & MICROSYSTEMS

7 March 2013

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AFOSR/RTD***

Integrity ★ Service ★ Excellence

Air Force Research Laboratory

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE 07 MAR 2013		2. REPORT TYPE		3. DATES COVERED 00-00-2013 to 00-00-2013	
4. TITLE AND SUBTITLE Mechanics of Multifunctional Materials and Microsystems				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Office of Scientific Research ,AFOSR/RTD,875 N. Randolph,Arlington,VA,22203				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES Presented at the AFOSR Spring Review 2013, 4-8 March, Arlington, VA.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 59	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			



2013 AFOSR SPRING REVIEW 3002B PORTFOLIO OVERVIEW



NAME: B. L. (“Les”) Lee

BRIEF DESCRIPTION OF PORTFOLIO:

Basic science for *integration* of *emerging materials* and *micro-devices* into future Air Force *systems* requiring *multi-functional design*

LIST OF SUB-AREAS:

- **Design of *Autonomic/Self-Sustaining* Systems;**
- **Design of *Reconfigurable* Systems;**
- Fundamentals of Mechanics of Materials;*
- Life Prediction (Materials & Micro-devices);*
- Sensing, Detection & Self-Diagnosis;*
- Self-Healing, Remediation & Structural Regeneration;*
- Self-Cooling & Thermal/Irradiation Management;*
- Energy Transduction & System Integration;*
- Actuation, Morphing & Threat Neutralization;*
- Engineered Bio/Nano/Info-materials*

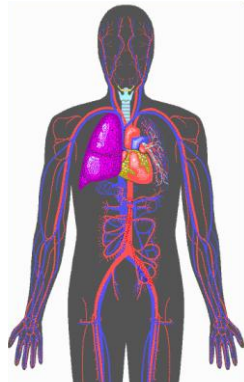


INSPIRED BY BIOLOGY...

*Creating a Synthetic **Autonomic** System*



AUTONOMIC RESPONSE



Autonomy:

***The ability to function in an
independent and automatic
fashion***

11

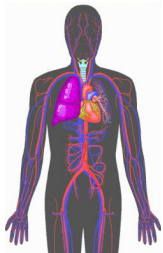


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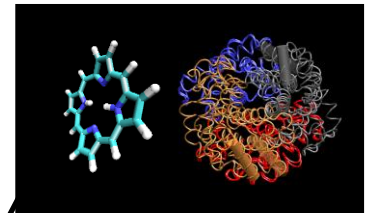
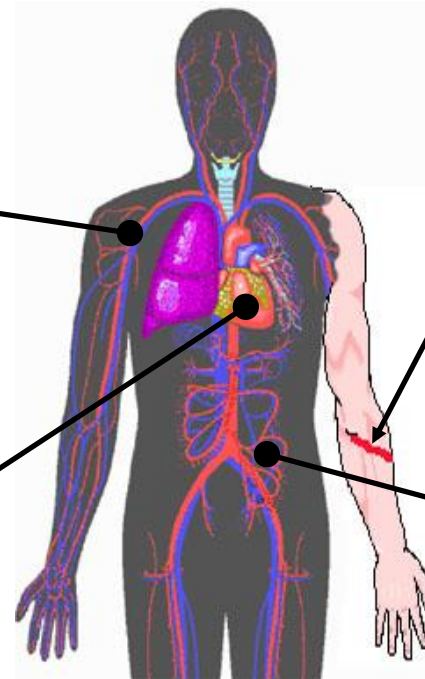
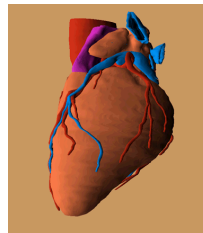


FUNCTIONS OF INTEREST



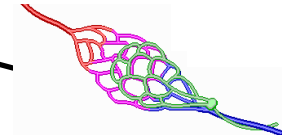
Self-Regulating Function

Active Regulation



Self-Generating Function

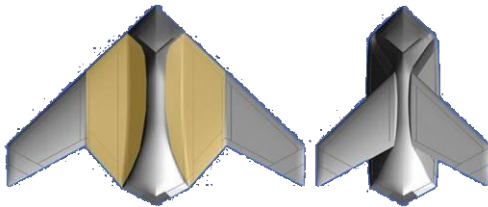
Mesoporous Networks



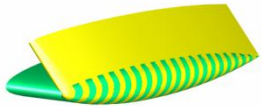
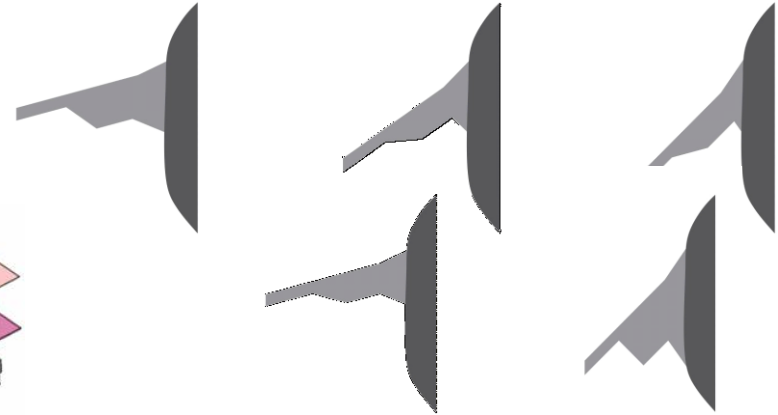


MORPHING AIRCRAFT

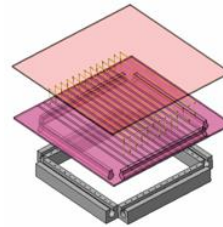
Source: AFRL/RB



Concepts



Enablers



Mechanization

Flexible Skins

Adaptive Structures

**Moving Beyond Swept Wing
Large Scale Area Changes
Showing It Can Be Done!**



**Wind Tunnel Tests
NASA 16 Ft Transonic Dynamics Tunnel**

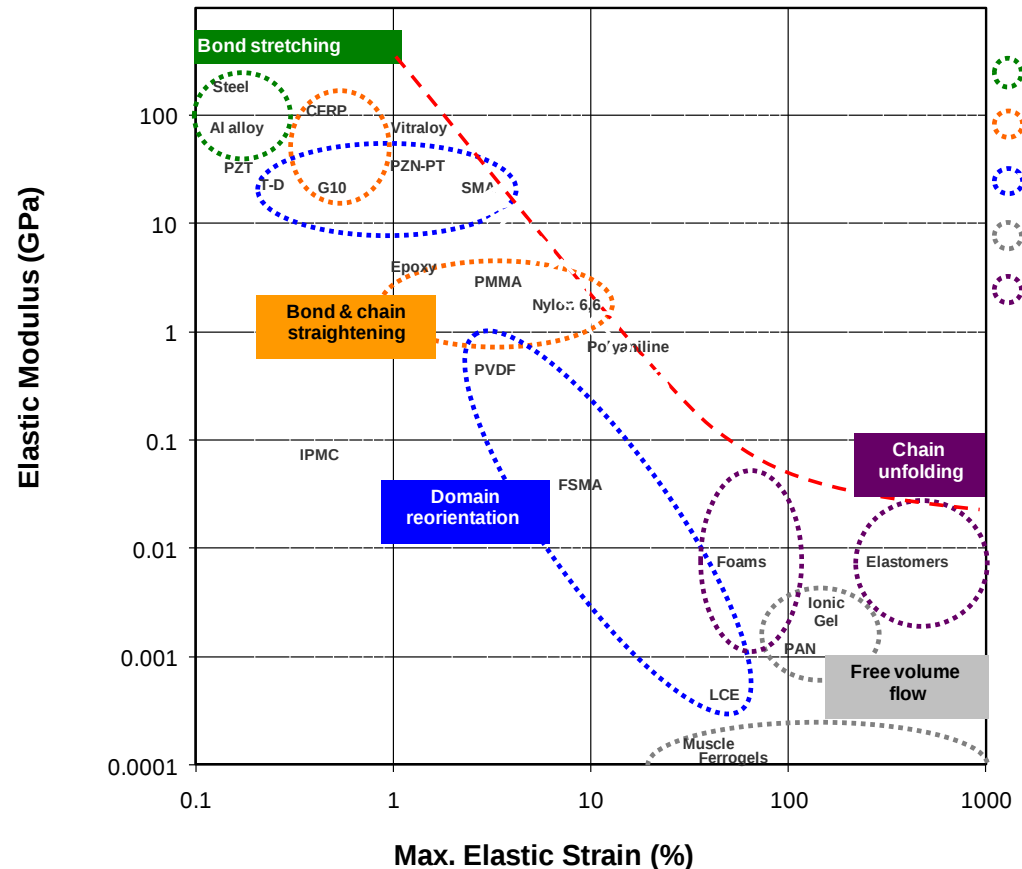
A First In Aviation History



ADAPTIVE STRUCTURES: TECHNICAL CHALLENGES



- Structural materials are made to NOT deform,
- Those that deform by **mechanization**, add weight and complexity
- **Reconfiguring** is easy on land, but not air, under sea, or in space
- Structural materials made to **deform on demand** with **minimized weight and complexity** is a key technology.



G. McKnight (HRL, Inc.)

Common materials cannot achieve simultaneous high stiffness and large deformation



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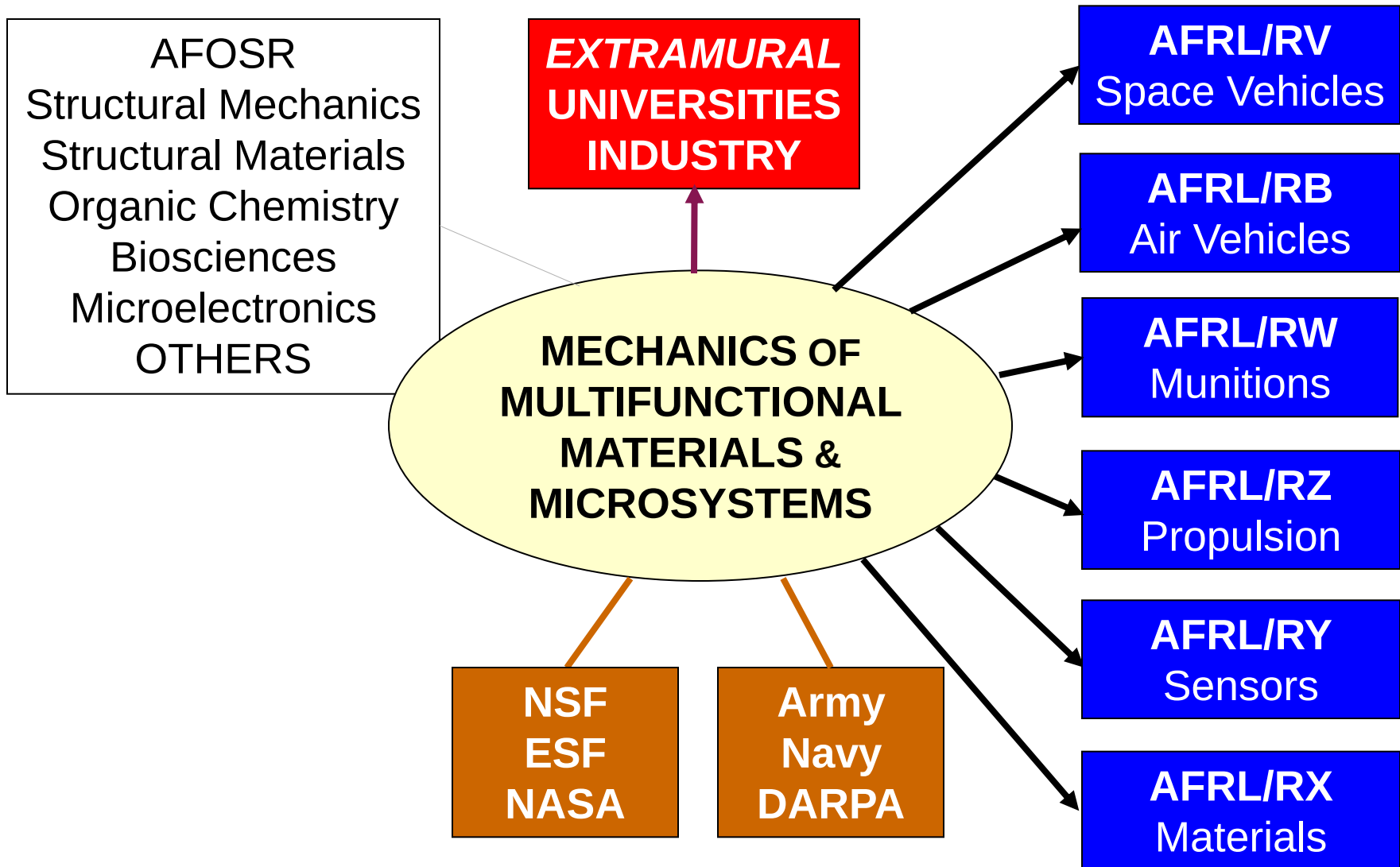
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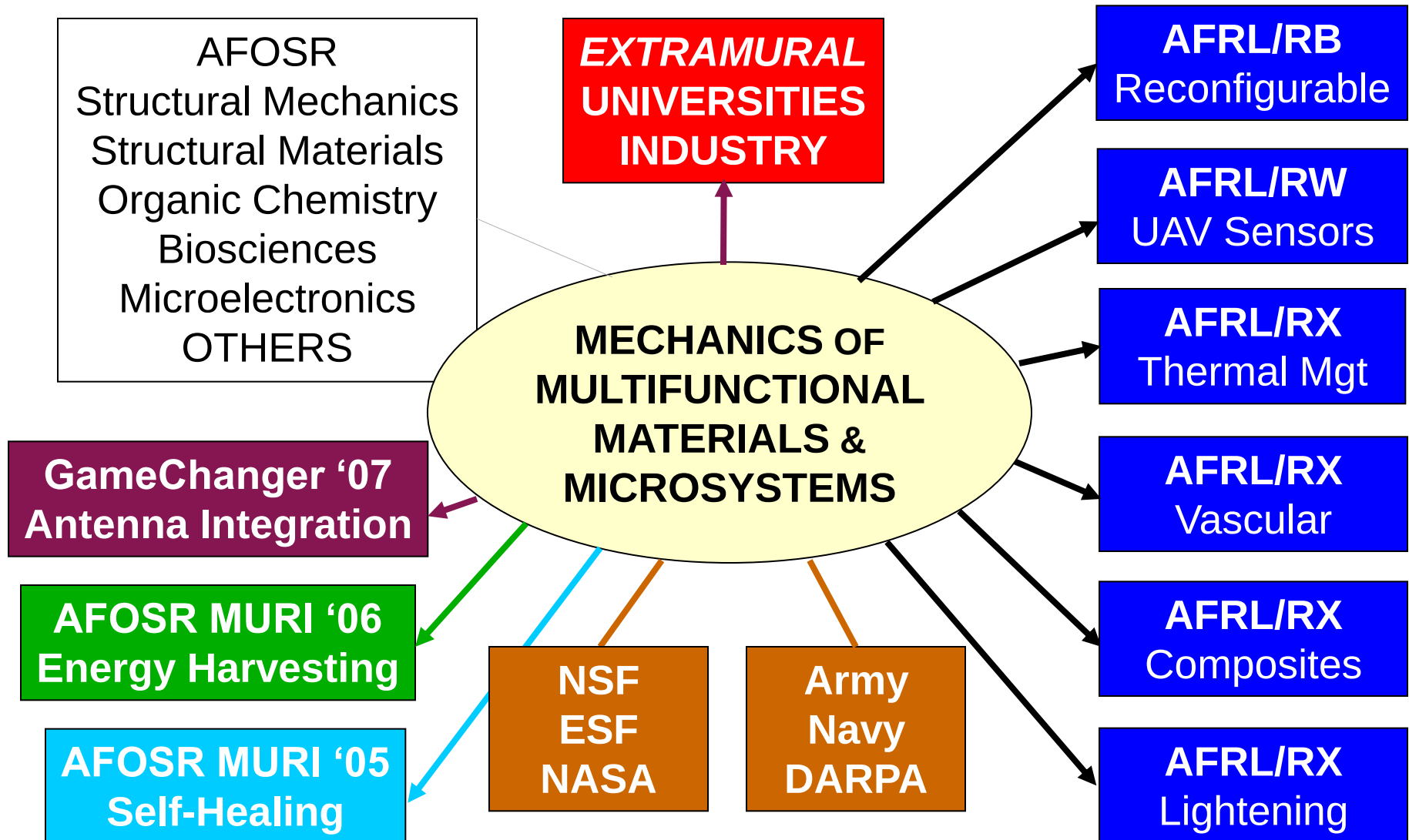


PROGRAM INTERACTION



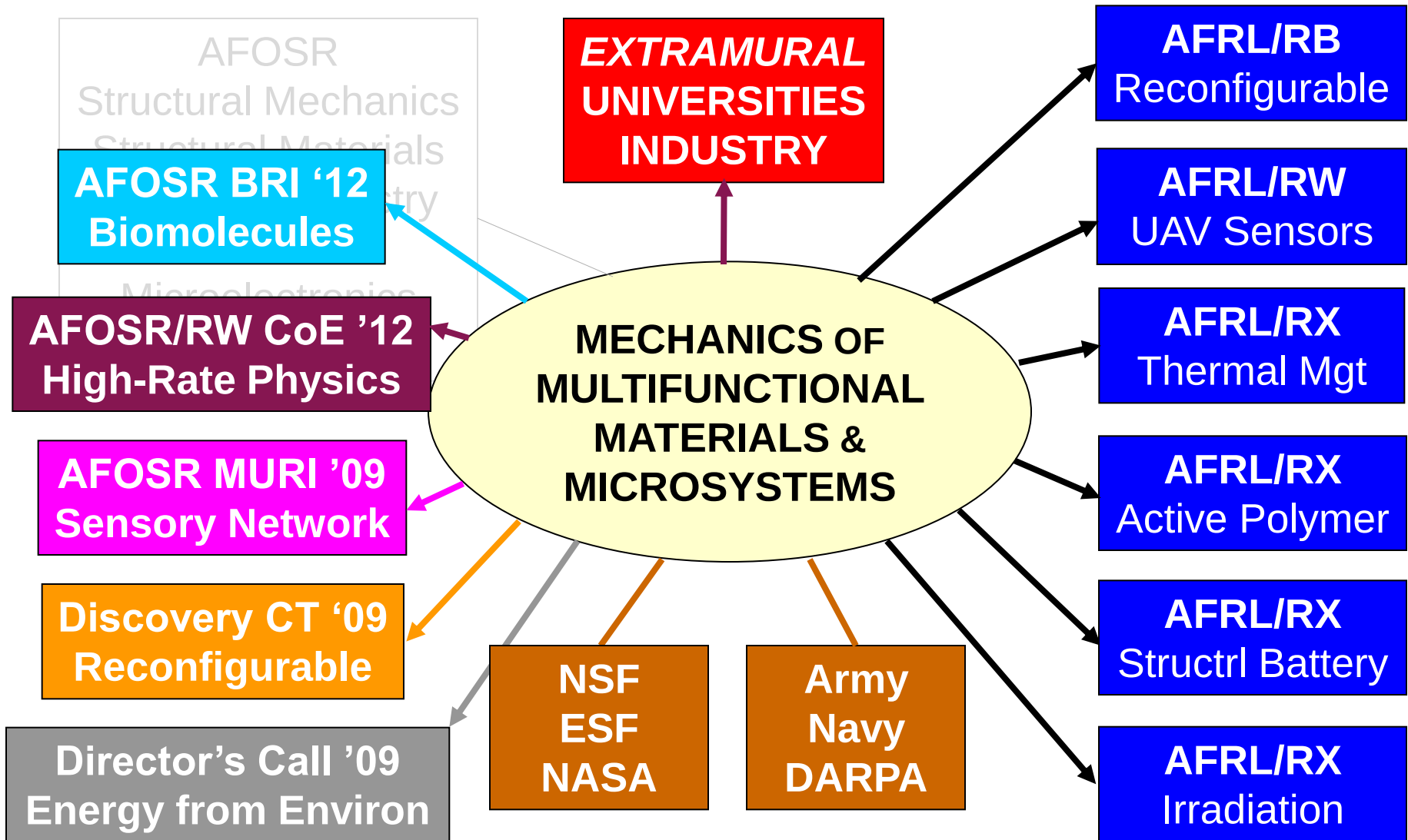


PROGRAM INTERACTION





PROGRAM INTERACTION





Scientific Challenges & Program Achievement



- **Self-healable** or **in-situ remendable** structural materials (*1st-ever program; world lead*)
- Microvascular composites for **continuous self-healing** and **self-cooling** systems (*1st-ever program; world lead*)
- Structural integration of **energy harvest/storage** capabilities (*1st-ever program on harvest capabilities; DoD lead*)
- Neurological system-inspired **sensing/diagnosis/actuation** network (*pot'l world lead*)
- **Biomolecules** for sensing and actuation (*pot'l world lead*)
- Mechanized material systems and micro-devices for **reconfigurable** structures (*DoD lead*)
- **Experimental** nano-mechanics (*DoD lead*)



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 – *Quantum improvement in survivability of aerospace structures & 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 – *Morphing wing aircraft & Neutralization of penetration threats*



PORTFOLIO TRENDS



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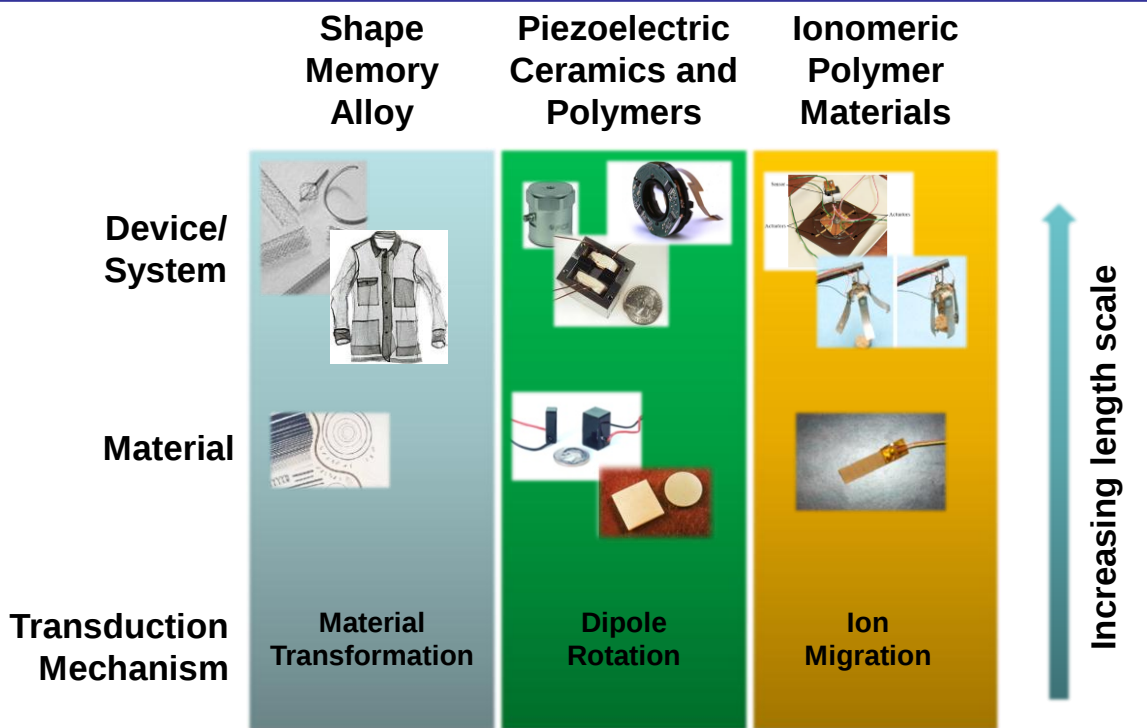
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- Energy** Transduction & System Integration; →
- Actuation**, Morphing & Threat Neutralization; ↗
- Engineered **Bio/Nano/Info-materials** ↗



ENGINEERED DEVICES: *BEYOND CURRENT VISION*



Traditional Transducer Materials



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

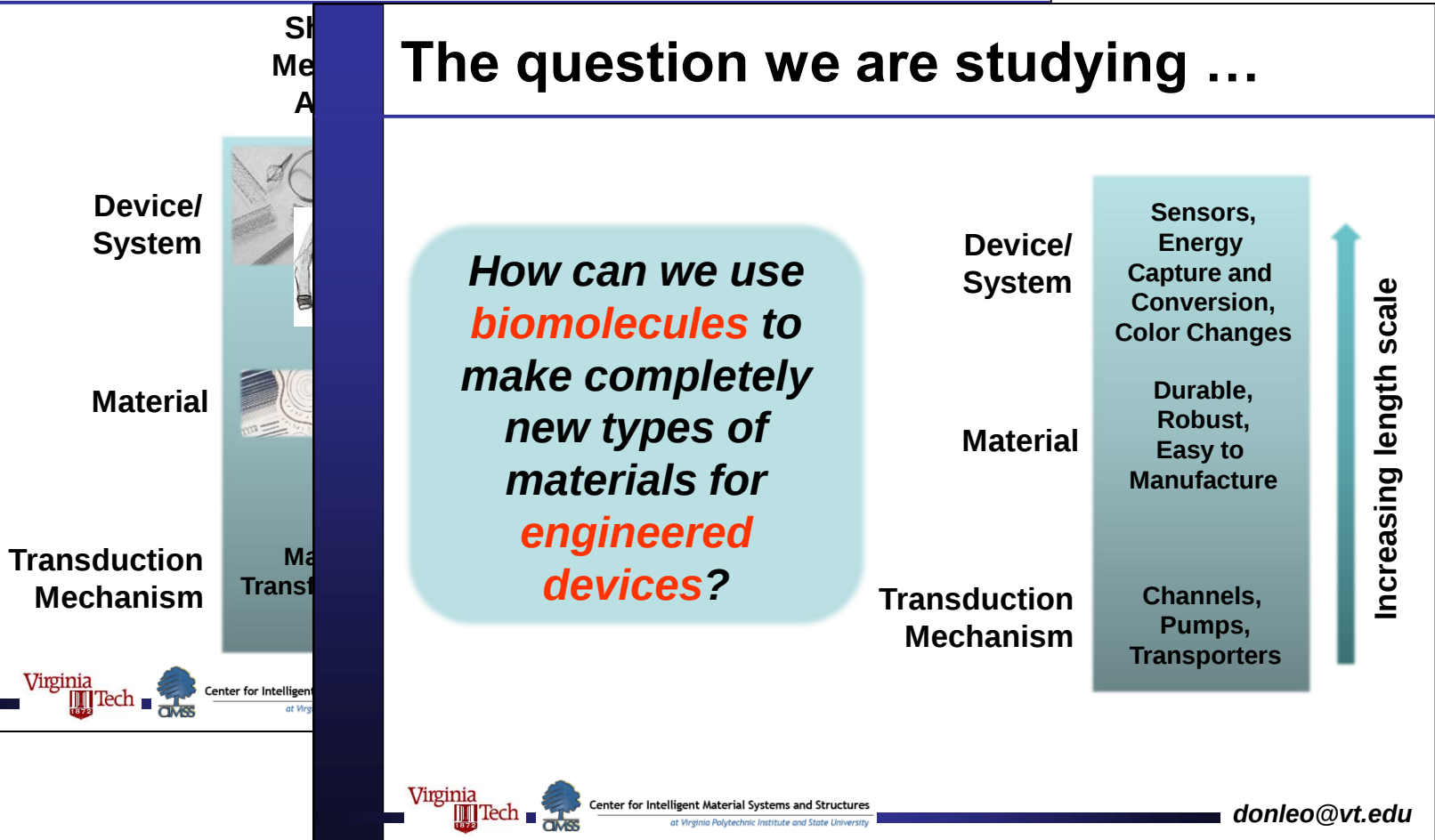
donleo@vt.edu



ENGINEERED DEVICES: BEYOND CURRENT VISION

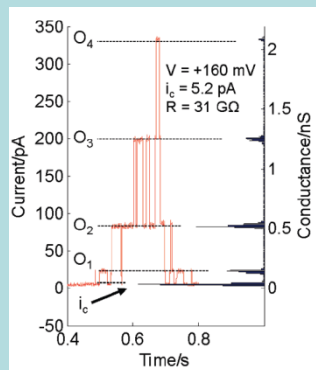
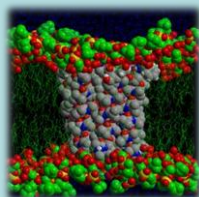
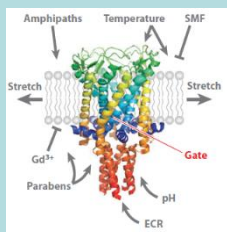


Traditional Transducer Materials

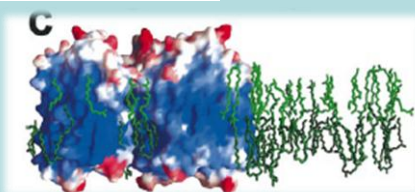




BRI'12 - BIOMOLECULES FOR SENSING (VT/U TN/U MD/UIUC: Leo)

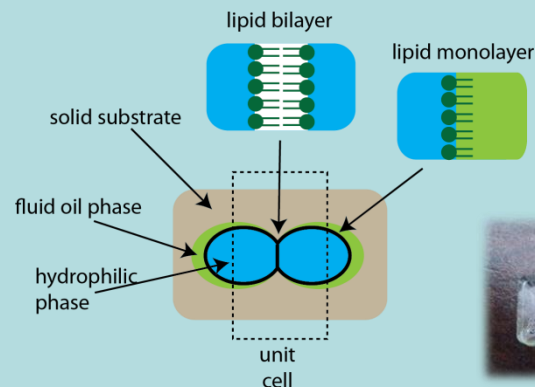


Gating response of the voltage-gated channel alamethicin to an applied potential.



Structure of the **mechanically-activated** channel MscL (top left), the **voltage-gated** channel alamethicin (top right), and the **light-activated** channel bacteriorhodopsin (bottom).

Over 3.5 billion years of evolution, nature has produced a highly diversified set of biomolecular transducers that exhibit a wide range of transduction properties.



A biomolecular unit cell utilizes the **stimuli-responsive** properties of biomolecules as a means of creating new transducer materials.

In the past two decades humans have been able controllably modify these transduction properties and incorporate them into durable material systems.

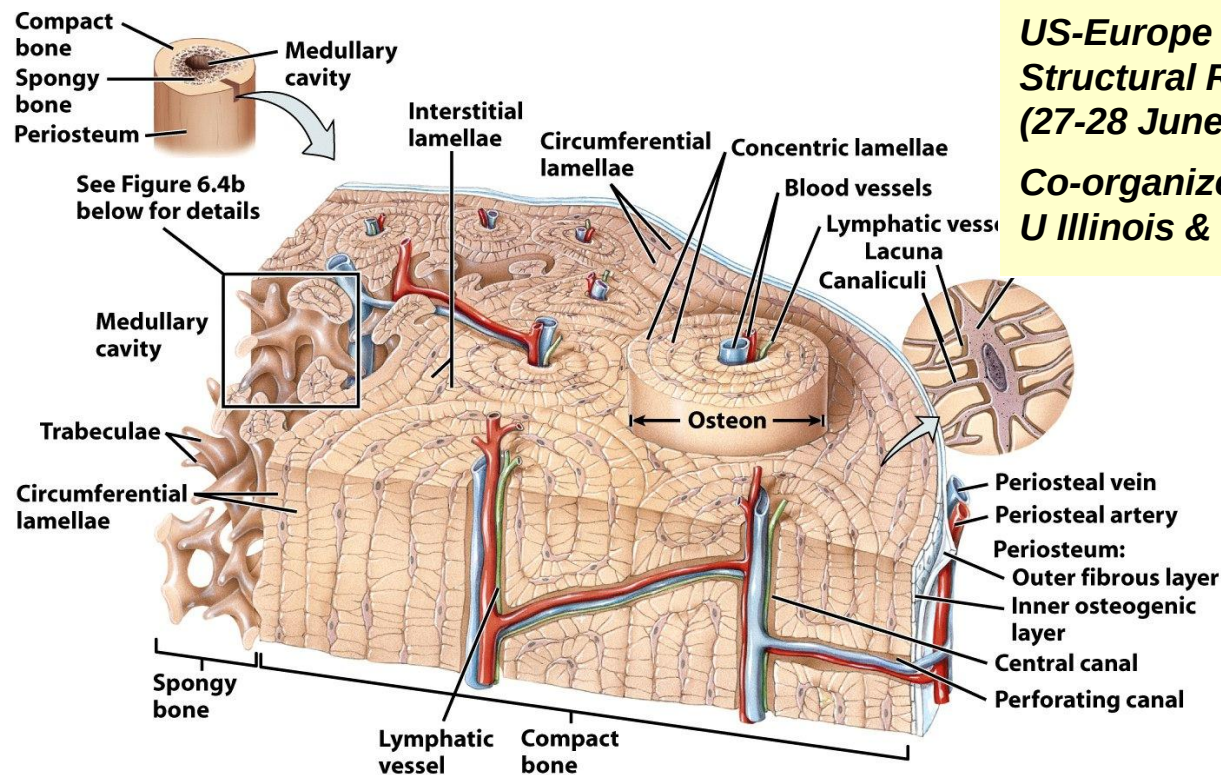
How can we utilize the stimuli-responsive properties of biomolecules to create a new class of transducer system?

Co-PM's: B. L. Lee, Hugh Delong



Design by Nature: BONE REMODELING

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



*US-Europe Workshop on
Structural Regeneration
(27-28 June 2012, Venice)*

*Co-organized by AFOSR, ARO,
U Illinois & Max Planck Inst.*

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



Transition from: Active Materials for Adaptive Structures



DCT'09: SUPER-CONFIGURABLE MULTIFUNCTIONAL STRUCTURES



Workshops:

- (a) AFRL-wide Brainstorming Discussion (Arlington, VA, 26 February 2007)
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- (d) AFOSR/ARO/DARPA Workshop on "Bio-inspired Networks" (Boston, MA, 29-30 November 2007)
- (e) AFRL-wide Round Table Discussion on DCT Topic (Eglin AFB, FL, 28 January 2008)



Objective

To establish new "morphing" aerospace structures capable of altering their **shape**, **functionality** and **mechanical properties** for **real-time optimization** in response to the changes in environments or operating conditions



Approach

- Develop new concepts for **structural reconfiguration**, **energy transduction mechanisms** and **system integration** allowing the combination of UAV and **space-deployable systems**.
- Identify new **adaptive materials**, **mechanized material systems** and **micro-devices** for sensing, communication or actuation.
- Model the influences of **morphology**, **dimensionality** and **topography** on the **multifunctional performance** and **manufacturability**.

Capability/Payoff

- Reduce **weight/size** and increase the **system efficiency** by incorporating multi-functionality into load-bearing structures
- Allow **mission-specific** and **real-time optimization** of multi-functional performance of military systems
- Potential systems to be impacted are: **unmanned aerial vehicles (UAV)**, **sensor platforms**, **dash/loiter theatre dominance platforms**, **space deployable systems**, etc.

Programs Involved

Mechanics of Multifunctional Materials & Microsystems;
Structural Mechanics;
Polymer Composites;
High Temperature Materials 43



Transition from: Active Materials for Adaptive Structures



**DCT'09: SUPER-CONFIGURABLE
MULTIFUNCTIONAL STRUCTURES**

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Transition from: Active Materials for Adaptive Structures



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Objective

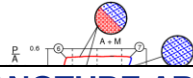
To establish new "morphing" aerospace structures capable of altering their **shape, functionality** and **mechanical properties** for **real-time optimization** in operation.



CELLULAR SHAPE MEMORY STRUCTURES (U Mich: Triantafylli)

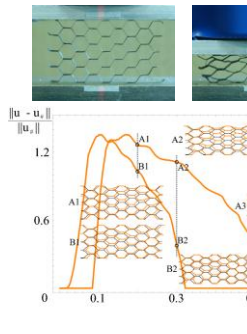
Objectives:

- To design better actuators/morphing devices using shape memory alloy honeycomb which combines cellular structures and mono



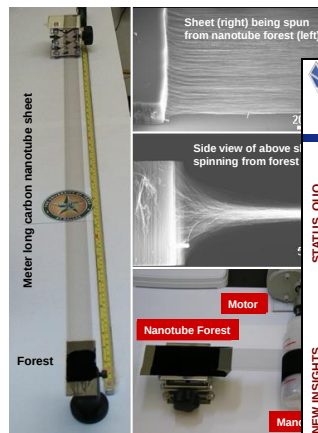
Capability/Payoff

- Reduce **weight/size** and increase the **stiffness** incorporating multi-functionality into load bearing structures
- Allow **mission-specific** and **real-time** change in functional performance of military systems
- Potential systems to be impacted are: **UAVs** (UAV), **sensor platforms**, **data dominance platforms**, **space deployment**



NANOTUBE ARTIFICIAL MUSCLE (U Texas Dallas: Baughman)

- ❖ Forest-drawn carbon nanotube sheets have higher specific strength than steel.



REVERSIBLE SHAPE MEMORY (Syracuse U / U CO: Mather)

MAIN ACHIEVEMENTS:

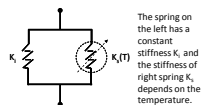
- Demonstrate two-way shape memory effects assisted by external force

Current Impact

- First free-standing two-way SMP based on

- Commonly Used Shape Memory Polymers (SMP)**
 - One-way shape memory (SM) effects
 - Not being able to recover the temporary shape
 - No design tools available
 - Two-way Shape Memory Polymers**
 - Two-way SM effects using switching between two stable states
 - No two-way SM due to intrinsic material property change
 - Two-way SMPs Applications**
 - Require combinatorial methods for material synthesis, modeling, and design.

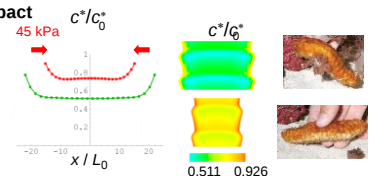
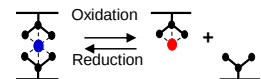
- Two-Way SMP by the Concept of Opposing Microstructural-Scale Spring**
 - Two opposing spring can generate motions if one or both of them can change properties as temperature changes
 - Opposing spring can be realized through material/structure design at micro-scale.



HOW IT WORKS
• Stretched in stress • Oppos reversible free effect is fully

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.



Transition to: Multifunctional Design of Morphing Air Vehicles



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BIRD-LIKE MORPHING WING

Courtesy of D. Lentink (Stanford U)

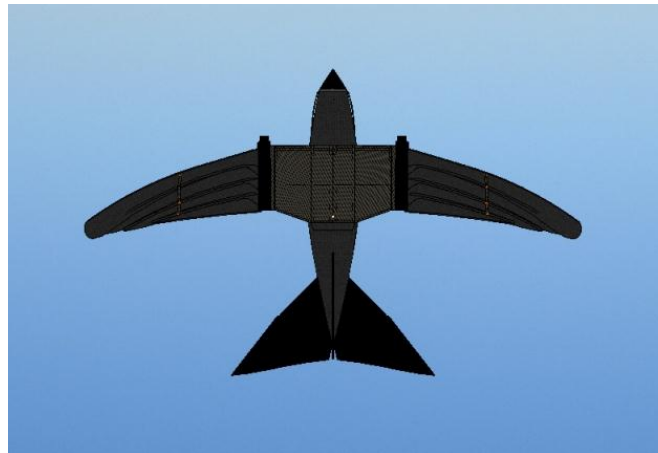


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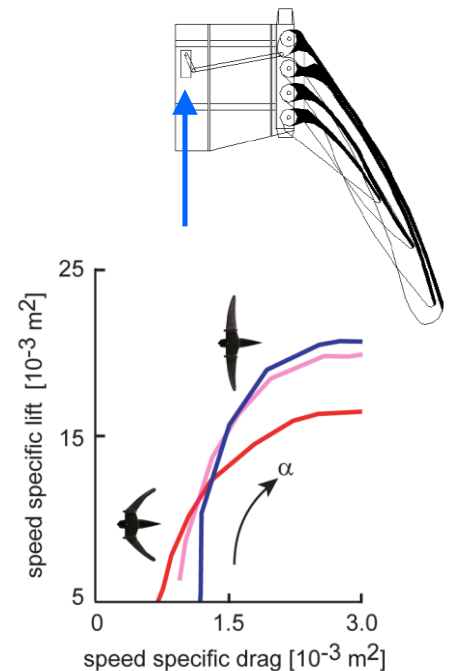
Programs In

Mechanics of Multifunctional Materials & Mechanisms
Structural Mechanics
Polymer Composites
High Temperature Materials



1st Bird-like Morphing UAV (TU Delft-led team):

- Design of a **morphing wing** with **feathers** inspired by **birds**.
- A servo sweeps the first feather back and forth with a pushrod. The other feathers are connected with a **parallel mechanism** to the first feather and follow.
- The 50cm long wing is built of **super-thin light-weight carbon fiber composites** with the plane weight of 100 gram.
- Successfully flew in an impressive wind force 5-6.





Transition to: Multifunctional Design of Morphing Air Vehicles



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- Model the influences of **morphology, dimensionality** and on the **multifunctional performance and manufacturability**



Objective:

To achieve **multifunctional design** of **morphing air vehicle** as an **autonomic system** (in collaboration with the expertise in *biomimetics, dynamics and control*)

BIRD-LIKE MORPHING WING

Courtesy of D. Lentink (Stanford U)



Capability/Payoff

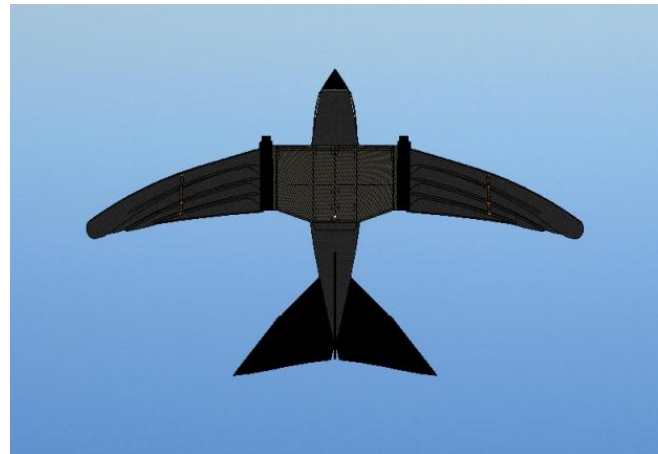
- Reduce **weight/size** and increase the **system efficiency** by incorporating multi-functionality into load-bearing structures
- Allow **mission-specific** and **real-time optimization** of multi-functional performance of military systems
- Potential systems to be impacted are: **unmanned aerial vehicles (UAV)**, **sensor platforms**, **dash/loiter theatre dominance platforms**, **space deployable systems**, etc.

Programs In

Mechanics of Multi
Materials & Mic
Structural Mechanic
Polymer Composite
High Temperature M

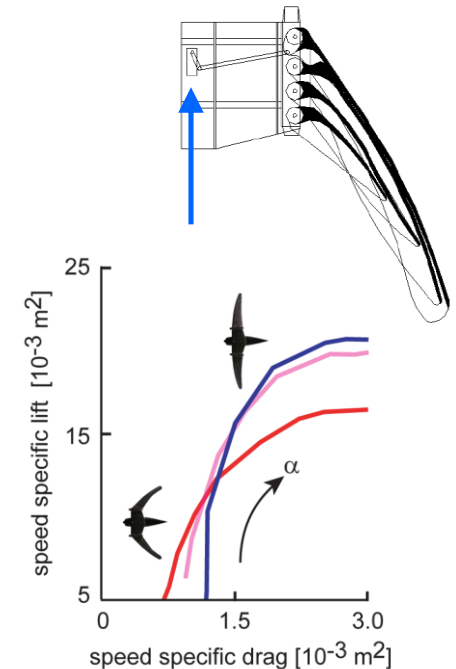
New Focus:

- ❖ Morphing air vehicles capable of altering the **geometry**, **surface area** and **mechanical properties** of wing structures
- ❖ Mimicking "**muscular-skeletal**" **system** of **bird wings**
- ❖ Deploying **mechanized active materials** and **computational metamaterials** for structural reconfiguration.



1st Bird-like Morphing UAV (TU Delft-led team):

- Design of a **morphing wing** with **feathers** inspired by birds.
- A servo sweeps the first feather back and forth with a pushrod. The other feathers are connected with a **parallel mechanism** to the first feather and follow.
- The 50cm long wing is built of **super-thin light-weight carbon fiber composites** with the plane weight of 100 gram.
- Successfully flew in an impressive wind force 5-6.





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

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

TOPIC 1 BIOSENSING

[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.

Proposed for AFOSR-NSF Collaboration:
"Muscular-Skeletal System Inspired Reconfigurable Materials Design";
"Structural Regeneration & Remodeling"

Pot'l MURI or BRI



THE 2ND "MULTIFUNCTIONAL MATERIALS FOR DEFENSE" WORKSHOP

Theme: Sensing, Actuation & Energy Transduction

In conjunction with:

The 2012 Annual Grantees'/Contractors' Meeting for AFOSR Program on "Mechanics of Multifunctional Materials & Microsystems"



**30 July-1 August 2012
Hilton Arlington Hotel, Arlington, VA**



Workshop Co-Chairs:

Gregory Reich (AFRL/RBSA)
William Nothwang (ARL/SEDD)
James Thomas (NRL)

Organizing Committee:

B.-L. ("Les") Lee (AFOSR), Co-Chair
David Stepp (ARO), Co-Chair
Ignacio Perez de Leon (ONR), Co-Chair
William Baron (AFRL/RBSA)
Jeff Baur (AFRL/RXBC)
Mark Derriso (AFRL/RBSI)
Gregory Reich (AFRL/RBSA)
William Nothwang (ARL/SEDD)
Daniel O'Brien (ARL/WMRD)
James Thomas (NRL)





PORTFOLIO OVERVIEW



NAME: B. L. ("Les") Lee

BRIEF DESCRIPTION OF PORTFOLIO:

Basic science for integration of emerging materials and micro-devices into future Air Force systems requiring multi-functional design

LIST OF SUB-AREAS:

- Design of **Autonomic/Self-Sustaining** Systems;
- Design of **Reconfigurable** Systems;
- Fundamentals of Mechanics of Materials;**
- Life Prediction (Materials & Micro-devices);**
- Sensing, Detection & Self-Diagnosis;**
- Self-Healing, Remediation & Structural Regeneration;**
- Self-Cooling & Thermal/Irradiation Management;**
- Energy Transduction & System Integration;**
- Actuation, Morphing & Threat Neutralization;**
- Engineered Bio/Nano/Info-materials**



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Energy Transduction & System Integration;
Actuation, Morphing & Threat Neutralization;
Engineered *Bio/Nano/Info*-materials

PI's & Co-PI's:

Tsu-Wei Chou (U Del)

Yuntian Zhu (NCSU)

Ioannis Chasiotis (UIUC)

Liping Liu (Rutgers U)[^]

David Kisailus (UC Riverside)^{*}

Pablo Zavattieri (Purdue U)

Don Leo (VA Tech)[#]

S. Andrew Sarles (U TN)

Sergei Sukharev (U MD)

Narayan Aluru (UIUC)

[^] YIP; ^{*} HBCU/MI; [#] BRI



PORTFOLIO OVERVIEW



NAME: B. A.

BRIEF DES

Basic science
into future

LIST OF SU

➤ Design

➤ Design

Fundamen

Life Predic

Sensing, D

Self-Healin

Self-Coolin

Energy Tra

Actuation,

Engineered Bio/Nano/Info-materials

Subject:

Thin Flexible CNT Composites

**>> Compliant Nano-spring Interfaces
Designing Structures for Functional Materials
Damage-tolerant Biological Composites**

>> Biomolecular Materials for Sensing & Actuation

>> New

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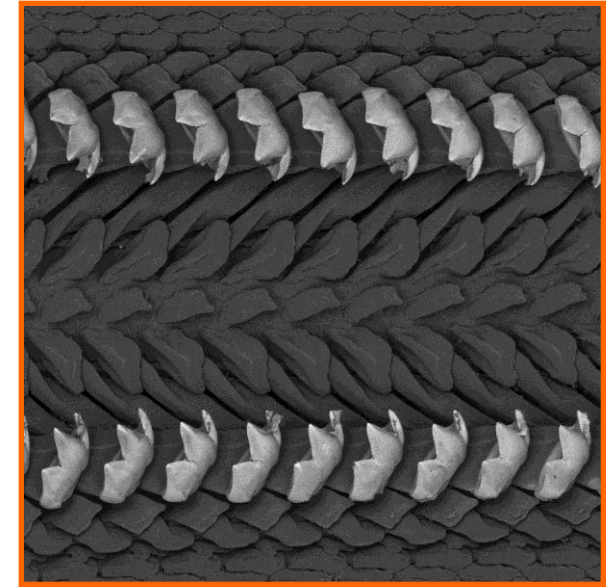
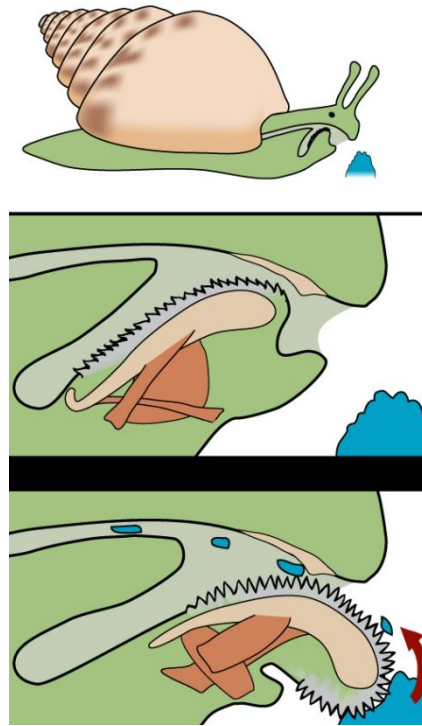
Sergei Sukharev (U MD)

Narayan Aluru (UIUC)

^ YIP; * HBCU/MI; # BRI



DAMAGE TOLERANT BIOLOGICAL COMPOSITES (*UCR: Kisailus*)



Radular Teeth of Chiton (elongated mollusk):

- ❖ Ribbon-like structure covered with small **dentacles** for tearing food into pieces
- ❖ Composed of an nanocrystalline iron phosphate **core** with a magnetite **veneer edge**
- ❖ The deposited mineral phase is ultra hard and abrasion resistant and 4-fold modulus difference at **core-veneer interface** effectively deflects crack propagation

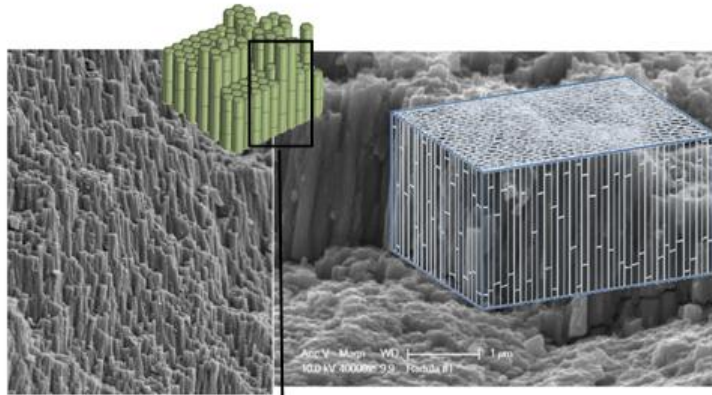




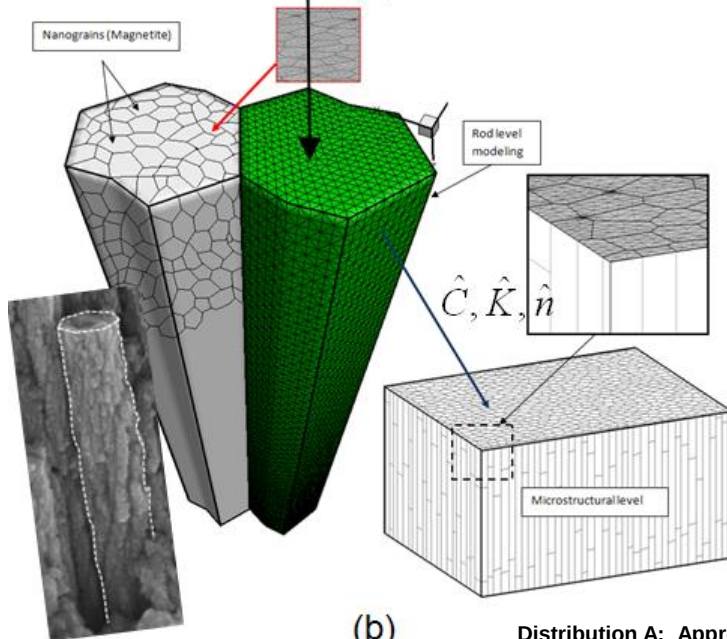
DAMAGE TOLERANT BIOLOGICAL COMPOSITES (*Purdue U: Zavattieri*)



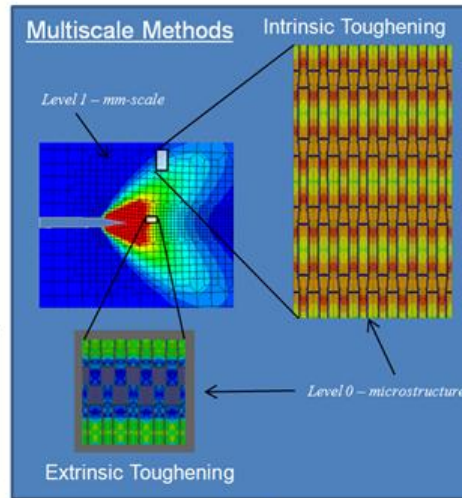
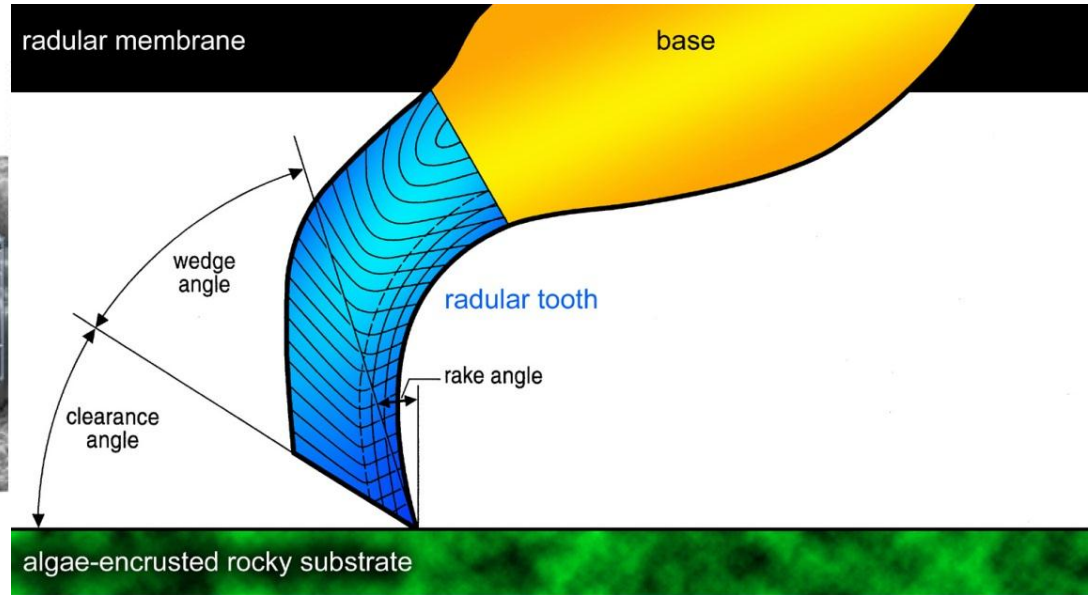
Relevance: Bio-inspired design of gears or abrasion-resistant materials



(a)



(b)



(c)

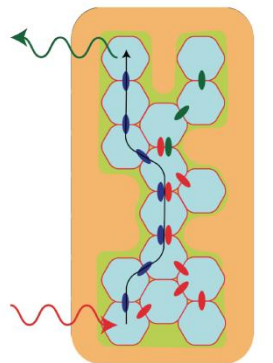
(a) Micromechanical model of rod like structure of radular tooth, including a potential RVE. (b) Hierarchical model to connect nano- to microscale. (c) Hierarchical model to connect the microscale to macroscopic fracture tests.



BRI'12 - BIOMOLECULES FOR SENSING (VT/U TN/U MD/UIUC: Leo)

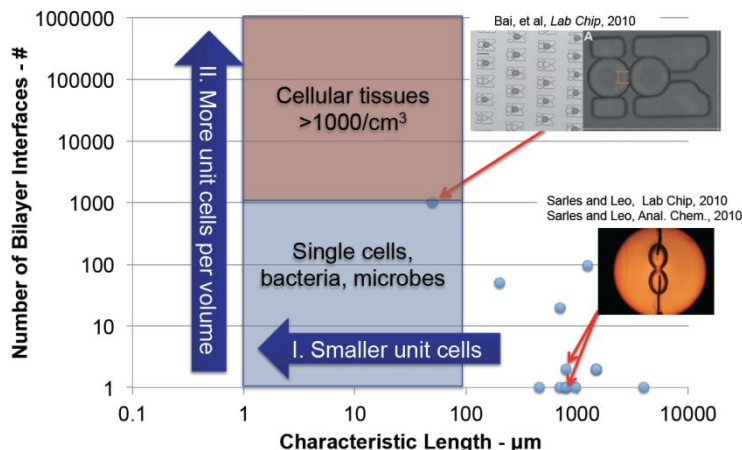


GOALS



Biomolecular Network

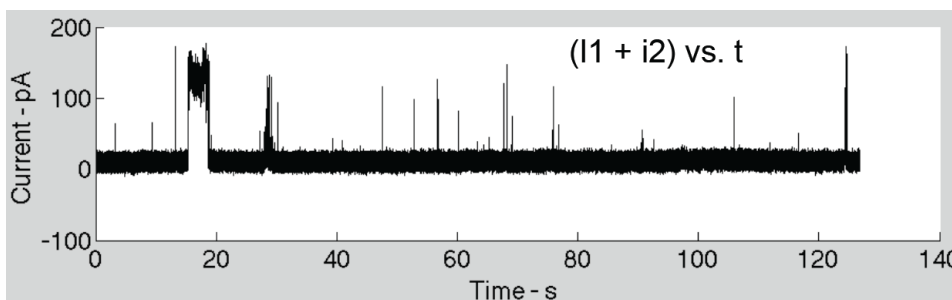
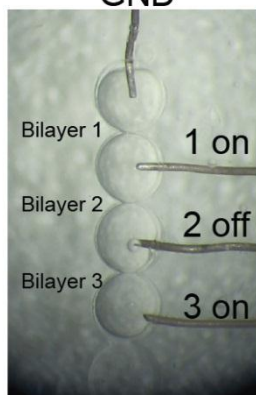
GND



Synthesis and Fabrication of Multi-Cellular Arrays:

- Autonomic, multifunctional behavior can only be achieved by incorporating large numbers of **stimuli-responsive “cells”** into the material.
- The program will establish in-depth understanding of the methods required for synthesizing and fabricating **multicellular material systems** with **characteristic length scales** less than 100 microns and **functional densities** that approach those of natural systems.

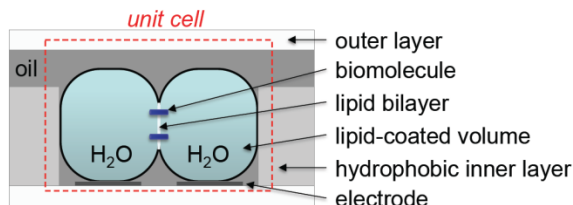
ACCOMPLISHMENTS



Fabricated a **four-cell material system** with a characteristic length scale on the order of 100s of microns.

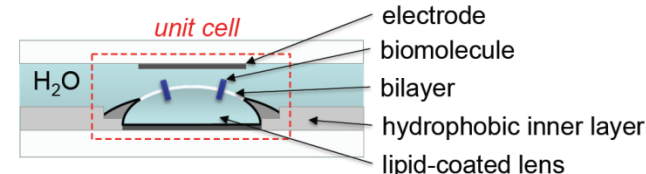
Measured **voltage-gated channel activity** across **multiple interfaces** in this four-cell material.

NEXT STEPS



Inject and arrange using microfluidics

Print and dewet



Begin the development of **injection** and **printing** methodologies for multi-cell arrays.



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Nakhiah Goulbourne (VA Tech)

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Frank Ko (U Brit Columbia)

Nicolaus Correll (U CO)

Ray Baughman (U Texas Dallas)

A. John Hart (U Mich)[^]

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Richard Vaia (AFRL/RXBN)

Greg Reich (AFRL/RBSA)

[^] YIP



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Self-Healin

Self-Coolin

Energy Tra

Actuation,

Engineered

Subject:

<< Reversible Shape Memory Polymer Composites

<< Ultra-Maneuverable Bat Technologies

<< Bio-inspired Reconfigurable Structures

Self-Assembly and Self-Repair of Structures

Artificial Muscles for Large Stroke & High Force

Morphing CNT Microstructures

Active Cells for Multifunctional Structures

Metamaterial Enhanced MEMS

Acoustic Metamaterials w Local Resonance

Ultrasonic Tunable Ultra-Damping Metamaterials

Macroscale Meta-Materials

Active Materials w Sensory & Adaptive Capabilities

Mechano-Responsive Polymer Systems

>> Mechanically-Adaptive Materials

Thermally-Activated Reconfigurable Systems

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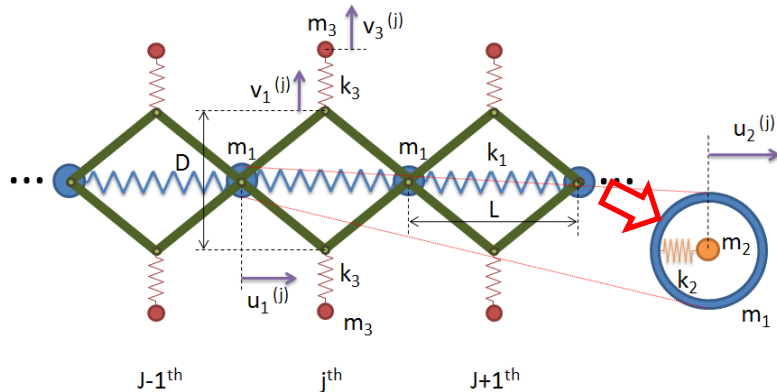
Greg Reich (AFRL/RBSA)

>> New; << Concluded

[^] YIP

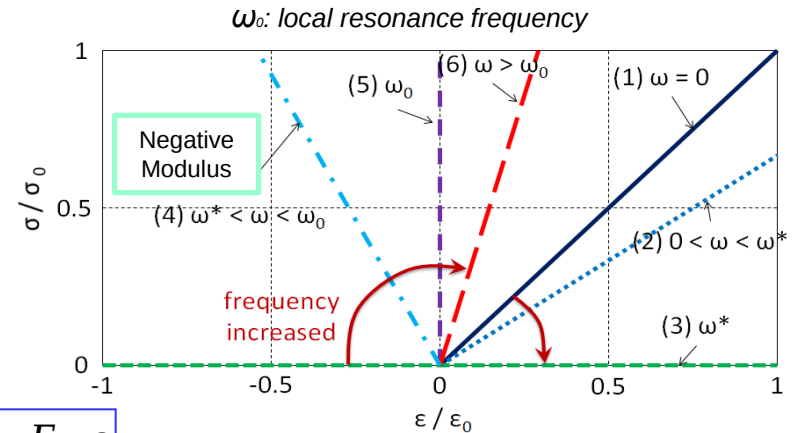


METAMATERIALS WITH NEGATIVE MODULUS (*Purdue U: Sun*)



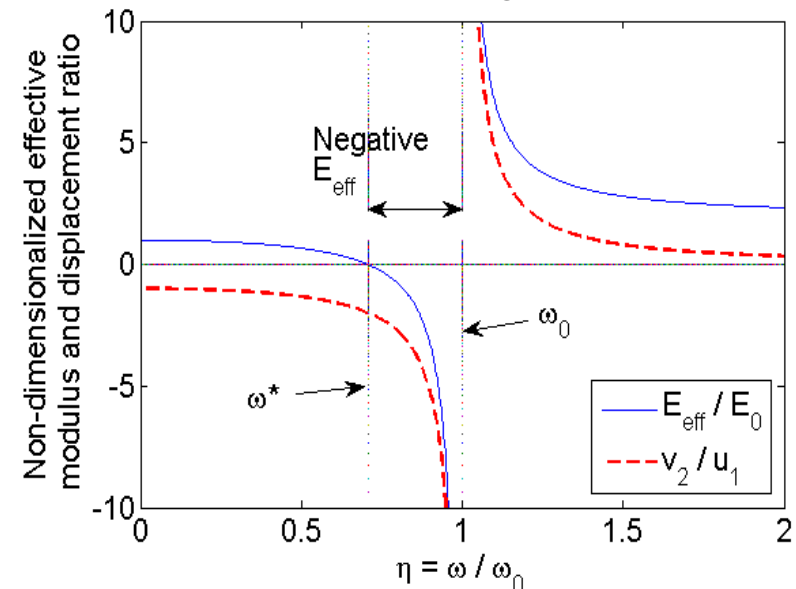
- A model is formulated for **acoustic** metamaterials with **locally resonant** microstructures.
- Under sinusoidal loading the **stress-strain relation** depends on the **frequency**.
- Near the local resonance frequency ω_0 of the side masses, the effective modulus is extremely large.
- The **effective Young's modulus** becomes **negative** in a certain frequency range.
- **Wave amplitude decays** when its frequency falls inside this **band gap**, especially if the frequency is near the frequency ω^* .
- At the lower bound frequency of the band gap ω^* , the effective modulus approaches zero.

Effective stress-strain relations



$$\sigma = E_{\text{eff}} \varepsilon$$

Effective Young's modulus



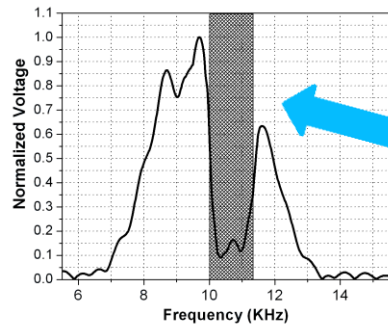
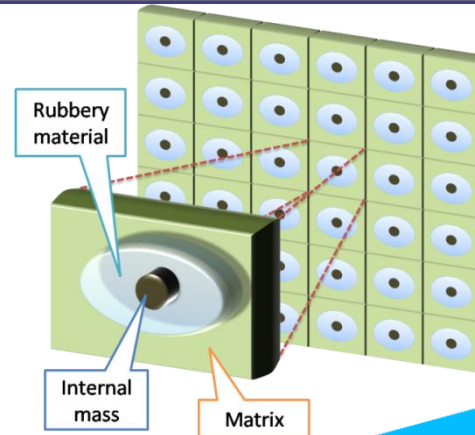


METAMATERIALS WITH NEGATIVE MODULUS (*Purdue U: Sun*)

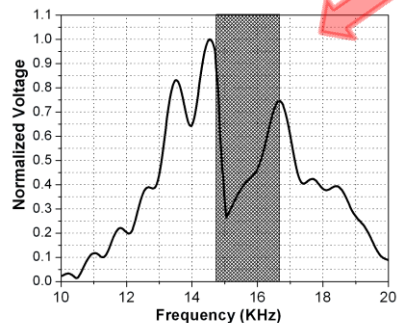


Goals

- Develop acoustic metamaterials for mitigating dynamic/impulsive loads
- Utilize the unusual wave propagation behavior of acoustic metamaterials in signal transmission, vibration isolation, and wave mode switching.



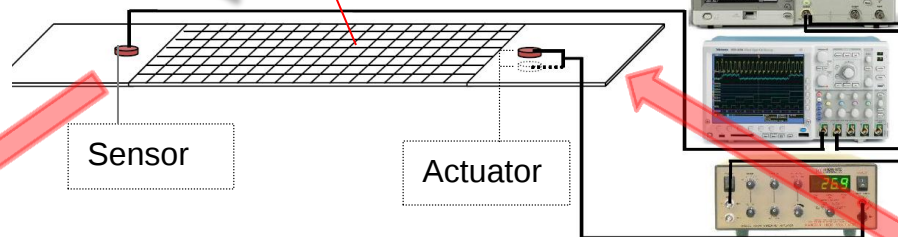
Output of In-plane Pulse



Output of Out-of-plane Pulse

Acoustic Metamaterial

Direction of Wave Propagation

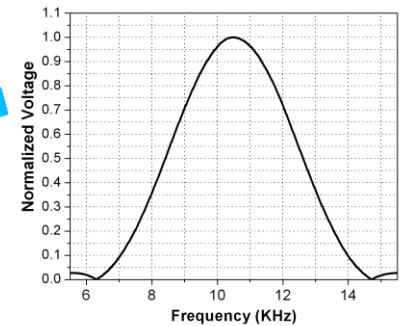


Experimental Setup

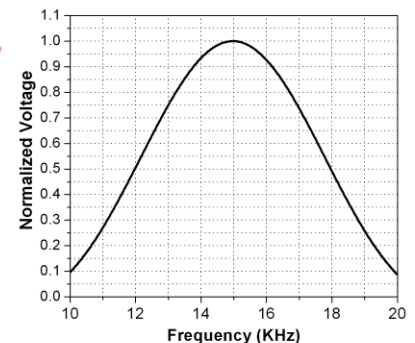
- Piezoelectric actuator patches were used for generating in-plane and out-of-plane waves
- Piezoelectric sensor patch was used for wave reception.

Result

- Significant **attenuation of wave amplitude** after passing through the metamaterial.
- **Band gap regions** of experimental results agree with that of the theoretical prediction (shaded regions).



Input of In-plane Pulse



Input of Out-of-plane Pulse



BAT-INSPIRED MORPHING WING (NextGen/Brown U/VPl: Joshi)



CURRENT STATE

- Reconfigurable hovering ultra-maneuverable **bat** technologies (RHUMBAT) offers potential benefits in operational robustness.
- Most research has focused on recreating three **degrees of freedom** (DOF's) assoc with this motion: **flap**, **lag**, and **feather**
- Small vehicle size and low inertia make **fine-scale control** required for envisioned missions difficult.

NEW INSIGHTS

- New unique approach considers **actuators** that are **distributed across the structure**.
- Provides detailed analysis for selection of **actuation DOF** using motion capture and revealing **complex morphologies of joints**.
- Wing membrane** characterization shows **thickness inhomogeneities** to be considered in materials selection.

Data Smoothing, Motion Trajectory

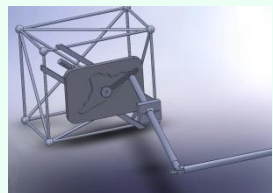
- Motion capture data improved
- Motion trajectory defined for humerus and radius



Right wing assembly

Skeletal Assembly

- Bones assembled in CAD
- CAD model guides mechanical design



Preliminary design

Robotic Wing

- 4 DOF
- High flapping frequency

MAIN ACHIEVEMENTS (Cont'd):

Inertial Measurement (IM)

- Acceleration and angular velocities recorded for straight and obstructed flights
- Dorsal mount miniature wireless IM Unit (IMU)



Biological Experiments

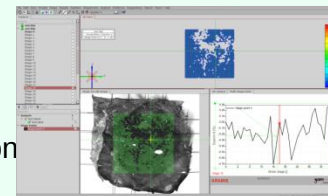
- Examined wing fiber under polarized light
- Guides constitutive model development



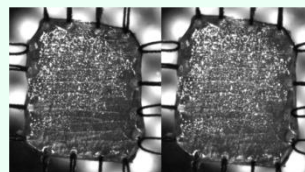
Wing fibers

Mechanical Characterization of Bat Membrane

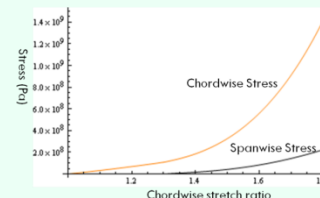
- Strain experiments
- Constitutive modeling
 - Fiber bundle dist.
 - Fiber bundle comp.
 - Base matrix corrugation
- Result satisfy material anisotropy property



Strain analysis



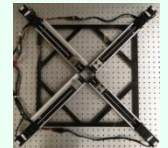
Biaxial loading



Simulated Stress-Strain Curve

Current Impact

- In depth understanding of **bat skeletal structure** and **skeletal dynamics** during flight
- Materials analysis** for structural & aerodynamic surfaces
- Translation of **bat dynamics** to **robotic system**



Improved suturing and biaxial setup

- High-fidelity models** for components and integrated structure representative of a bat-wing
- Quantitative evaluation of **flight performance, energy consumption / efficiency**
- Estimates of **weight, volume** and **geometry** of a **robotic bat-wing**
- Guidelines** to develop an autonomous, hovering, highly maneuverable, **bat-like MAV**

QUANTITATIVE IMPACT

END-OF-PHASE GOAL



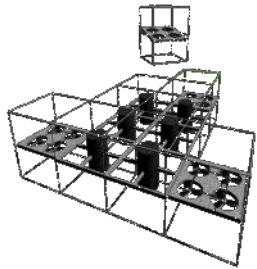
SELF-ASSEMBLY & SELF-REPAIR (U CO: Correll)



Objectives:

- Reconfiguration planning for **smart structures with embedded sensing, computation and actuation**
- Take into account **physical constraints** including gravity, wind and vibration
- **Enabling materials with the ability to self-reconfigure and self-repair**

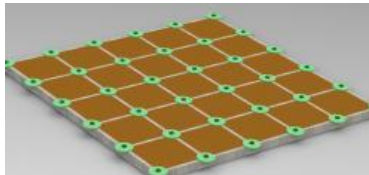
Smart Structures



Flying/self-mobility



External actuation



In-material sensing, computation and actuation

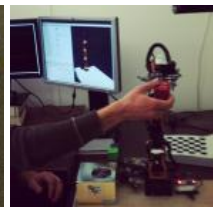
Approach:

- Combination of finite element analysis and real-time physics **simulation** with discrete search to find suitable reconfiguration paths.
- Embedding of intelligence for sensing and control of **internal/external actuators**

Achievements:

Platform development

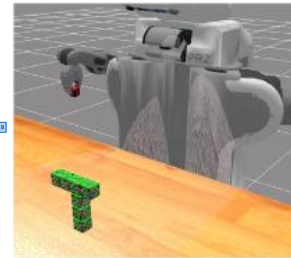
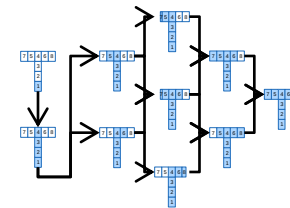
- Begun development of light-weight **in-air self-assembly test-bed**
- Begun development of **manipulation test-bed**
- Begun development of **variable stiffness material**



Light-weight in-air module; robotic assembly; variable stiffness material with embedded sensing/actuation

Reconfiguration planning

- Initial focus: **robotic assembly** under gravity constraints
- Discrete/Continuous **search framework** combining graph-based search, FEA and full-physics simulation



Assembly graph of a T-structure (left), full-physics simulation (right)

Perspectives:

- **Novel structural components** that can change their shape, function and appearance
- **Reconfigurable materials** to change function taking into account and in response to physical constraints



Transition to: Multifunctional Design of Morphing Air Vehicles



DCT'09: SUPER-CONFIGURABLE MULTIFUNCTIONAL STRUCTURES

Workshops:

- (a) AFRL-wide Brainstorming Discussion (Arlington, VA, 26 February 2007)
- (b) 6th AFOSR Workshop on "Multifunctional Aerospace Materials & Structures: Manufacturing Issues" (Seattle, WA, 18-19 September 2007)
- (c) AFOSR/SFIESF Workshop on "Adaptive Structures and Materials" (St. Maximin, France, 4-7 November 2007)
- (d) AFOSR/ARO/DARPA Workshop on "Bio-Inspired Networks" (Boston, MA, 29-30 November 2007)
- (e) AFRL-wide Round Table Discussion on DCT Topic (Eglin AFB, FL, 29 January 2008)



Objective

To establish new "morphing" aerospace structures capable of altering their **shape, functionality and mechanical properties** for **real-time optimization** in response to the changes in environments or operating conditions

Approach

- Develop new concepts for **structural reconfiguration, energy transduction mechanisms and system integration** allowing combination of UAV and space-deployable systems
- Identify new **adaptive materials, mechanized material**
- **micro-devices** for sensing, communication or actuation
- Model the influences of **morphology, dimensionality** and on the **multifunctional performance and manufacturability**



Objective:

To achieve **multifunctional design** of **morphing air vehicle** as an **autonomic system** (in collaboration with the expertise in *biomimetics, dynamics and control*)

BIRD-LIKE MORPHING WING

Courtesy of D. Lentink (Stanford U)



Capability/Payoff

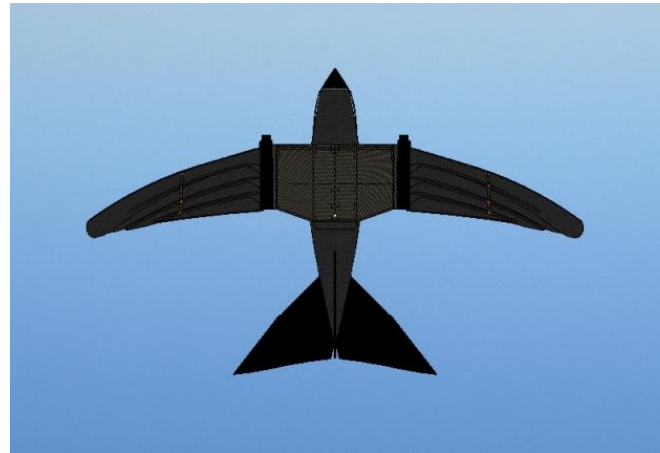
- Reduce **weight/size** and increase the **system efficiency** by incorporating multi-functionality into load-bearing structures
- Allow **mission-specific** and **real-time optimization** of multi-functional performance of military systems
- Potential systems to be impacted are: **unmanned aerial vehicles (UAV)**, **sensor platforms**, **dash/loiter theatre dominance platforms**, **space deployable systems**, etc.

Programs In

Mechanics of Multi
Materials & Mic
Structural Mechanic
Polymer Composite
High Temperature M

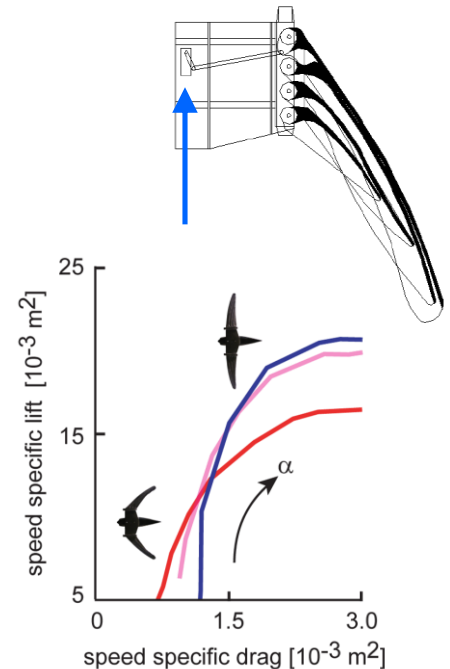
New Focus:

- ❖ Morphing air vehicles capable of altering the **geometry**, **surface area** and **mechanical properties** of wing structures
- ❖ Mimicking "**muscular-skeletal**" **system** of **bird wings**
- ❖ Deploying **mechanized active materials** and **computational metamaterials** for structural reconfiguration.



1st Bird-like Morphing UAV (TU Delft-led team):

- Design of a **morphing wing** with **feathers** inspired by birds.
- A servo sweeps the first feather back and forth with a pushrod. The other feathers are connected with a **parallel mechanism** to the first feather and follow.
- The 50cm long wing is built of **super-thin light-weight carbon fiber composites** with the plane weight of 100 gram.
- Successfully flew in an impressive wind force 5-6.





PORTFOLIO OVERVIEW



NAME: *B. L. (“Les”) Lee*

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LIST OF SUB-AREAS:

- **Design of *Autonomic/Self-Sustaining* Systems**
- *Design of Reconfigurable Systems;*
- Fundamentals of Mechanics of Materials;*
- Life Prediction (Materials & Micro-devices);*
- Sensing, Detection & Self-Diagnosis;*
- Self-Healing, Remediation & Structural Regeneration*
- Self-Cooling & Thermal/Irradiation Management*
- Energy* Transduction & System Integration;**
- Actuation, Morphing & Threat Neutralization;*
- Engineered Bio/Nano/Info-materials*

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Sven Bilén (Penn St U)
Michael Strano (MIT)
Max Shtein (U Mich) #
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Wonbong Choi (FL Int'l U)
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Hugh Bruck (U MD)
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Carmel Majidi (Carnegie-Mellon)^
Michael Durstock (AFRL/RXBN)
Benji Maruyama (AFRL/RXBN)
John Coggin (Prime Photonics)+
Shashank Priya (VA Tech)+

^ YIP; # PECASE; + STTR



PORTFOLIO OVERVIEW



NAME: B. A.

BRIEF DESCRIPTION

Basic science
into future

LIST OF SUBJECTS

➤ **Design**

➤ **Design**

Fundamental

Life Prediction

Sensing, Detection

Self-Healing

Self-Cooling

Subject:

<< **Energy Harvesting via Electrodynamic Tethers**
Environmental Hydrocarbon Harvesting via CNT
Energy Harvesting Textile Composites
Active Structural Fibers for Multif'l Composites
Vibration Suppression and Energy Harvesting
Nanoscale Based Thermal Energy Harvesting
Flexible Battery of Graphene-CNT Hybrid
Integrity of Energy Harvest/Storage Materials
Integrated Solar Cells for MAV Wings
>> << **Electrodes for Multifunctional Li-ion Battery**
>> **Energy Harvesting for Soft-Matter Machines**
Nanomaterials for Structural Batteries

Hybrid Energy Harvesting Systems

>> **New**; << **Concluded**

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Energy Transduction & System Integration;

Actuation, Morphing & Threat Neutralization;

Engineered Bio/Nano/Info-materials

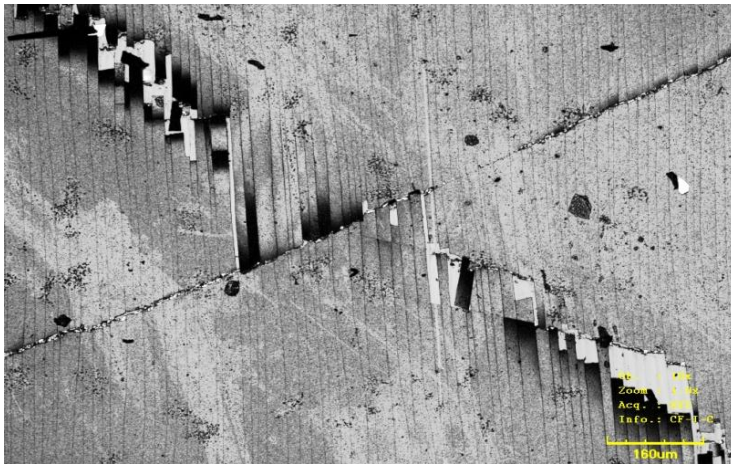


STRUCTURAL INTEGRITY OF ENERGY DEVICES (*UIUC: Chasiotis*)

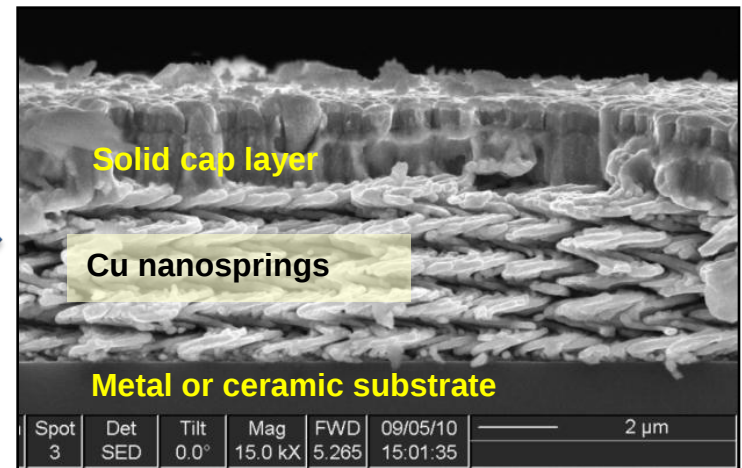


Challenges for Integration of Solar Cells & Batteries into Load-Bearing Composite Structures:

- Materials degradation of thin film solar cells and batteries during curing of the composite materials.
- Thermal mismatch** between thin films and the underlying structure generate high strains. As a result, the integrated structure could suffer **wavy blister** type **delamination** and **fragmentation failure**.
- Prior efforts to integrate thin film solar cells with CFRPs pointed out **0.3%** and **1% critical strains** for **performance reduction** and **fragmentation failure** respectively.
- Micron- or nano-scale springs** of metallic or ceramic thin films benefit from size effects to provide **compliant, yet strong and tough, multifunctional interface** (*A new grant initiated*) .
- High capacity battery electrodes are prone to **cracking** under stress upon lithiation.



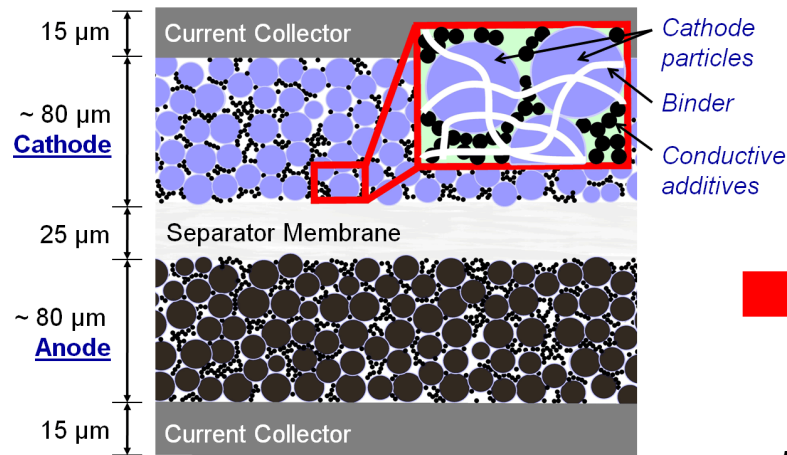
Fragmentation of a 2- μm thick ZnO/Si solar cell bonded on ($\pm 45^\circ$)₄ laminate loaded according to the arrows. The vertically parallel strips are ZnO/Si film fragments.



Film of nanosprings fabricated by glancing angle deposition (GLAD).



YIP'09 - LOAD BEARING BATTERIES (GA Tech: Yushin)

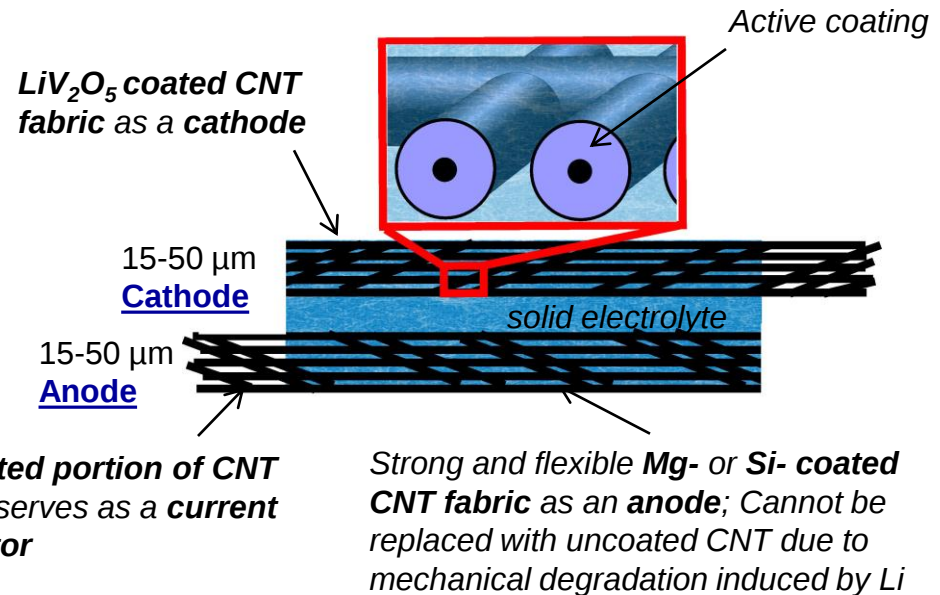


Cu current collector; Graphite anode with PVDF binder; LiMO_x cathode (M: Co, Mn, Ni)



Traditional Electrodes & Cell Architecture

- Low electrical conductivity
- Low thermal conductivity
- Heavy/bulky metal foils
- No mechanical strength

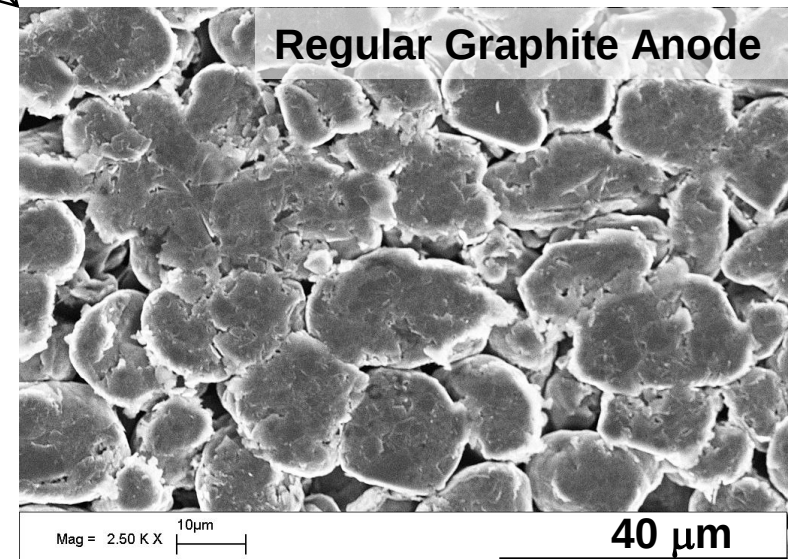
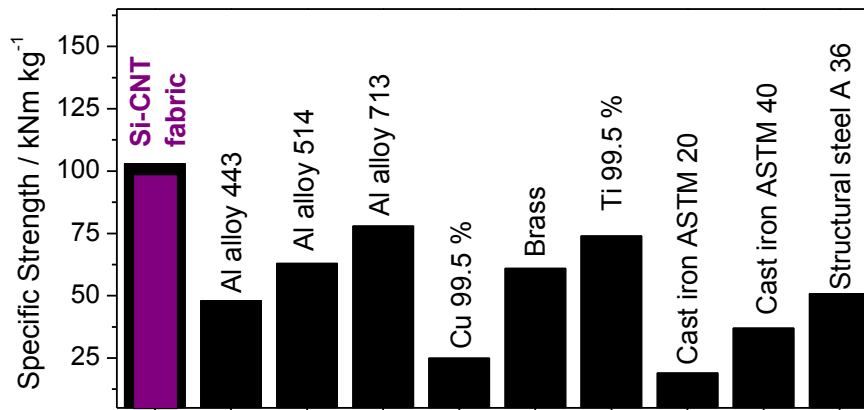
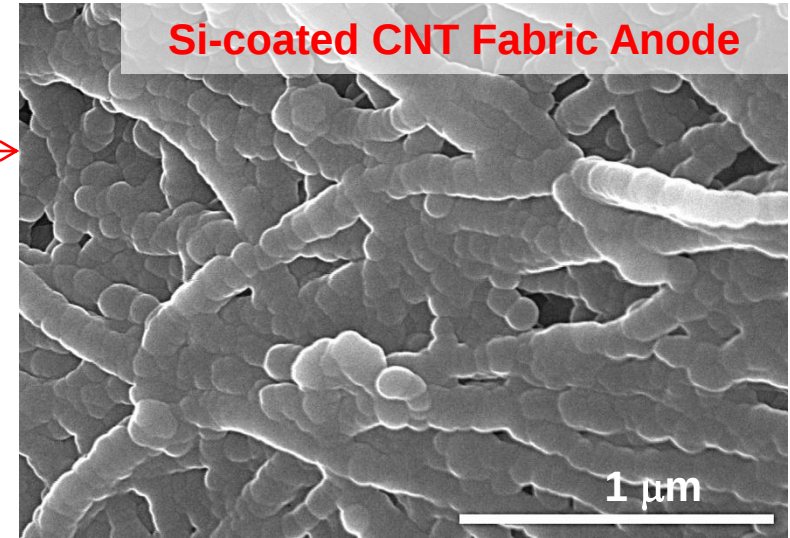
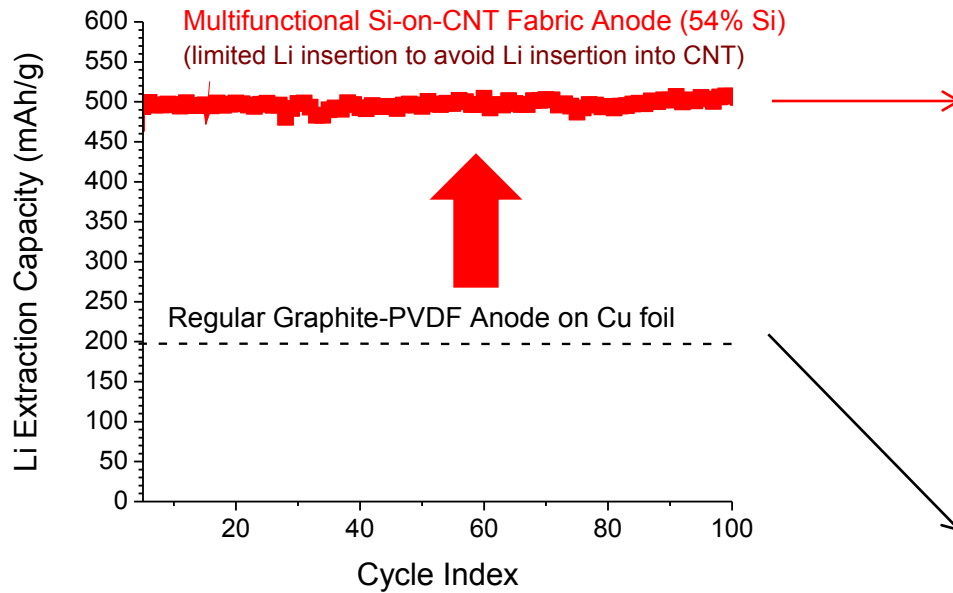


Multifunctional Nanocomposite Fabric for Electrodes & Current Collector

- Ultra-high electrical conductivity
- High thermal conductivity
- No metal foil current collectors needed
- High mechanical strength
- Enhanced safety (with solid electrolyte)



YIP'09 - LOAD BEARING BATTERIES (GA Tech: Yushin)





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Tom Hahn (UCLA)+
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Scott White (UIUC)
Jeffrey Moore (UIUC)

Jimmy Xu (Brown U)
Ajit Roy (AFRL/RXBT)
Abraham Stroock (Cornell U)
Noel Holbrook (Harvard U)
Patrick Kwon (Mich St U)
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Mary Frecker (Penn St U)
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^ YIP; + STTR



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Sensing, L

Self-Healin

Self-Cooli

Energy Tr

Actuation,

Engineere

Subject:

<< **Inkjet-Assisted Creation of Self-Healing Layers**
<< **Remendable Composites w Resistive Heating**

<< **Interfacial Self-Healing in Composites**
Regeneration & Remodeling of Composites

<< **Thermal Signature Reduction & EMI Shielding**
<< **Carbon Fiber Morphology for Thermal Materials**
Plant-mimetic Heat Pipes

New Generation of Perspirable Skin
Variable Thermal Conductivity Structures

Graphene Composites for Lightning Protection
Microvascular Systems for Mass/Energy Transport
>> **Multifunctional Poro-Vascular Composites**
>> **Composites under High Energy Irradiation**

>> **New**; << **Concluded**

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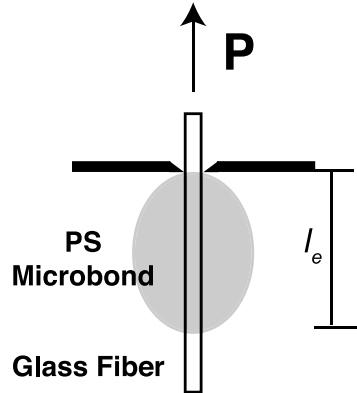
^ YIP; **+ STTR**



INTERFACIAL SELF-HEALING IN COMPOSITES (*UIUC: Sottos*)

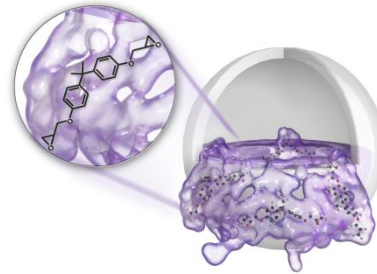


Single fiber microbond test

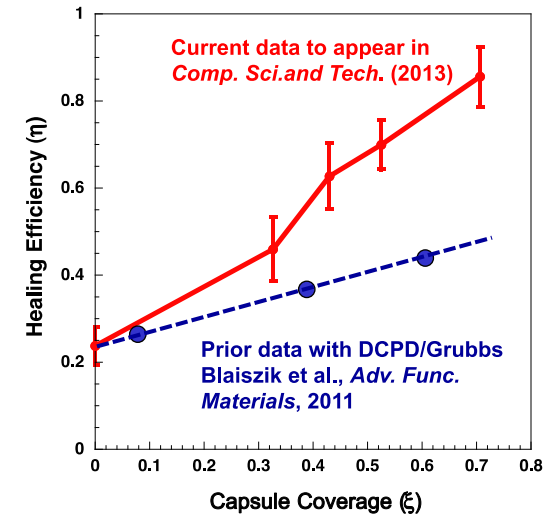
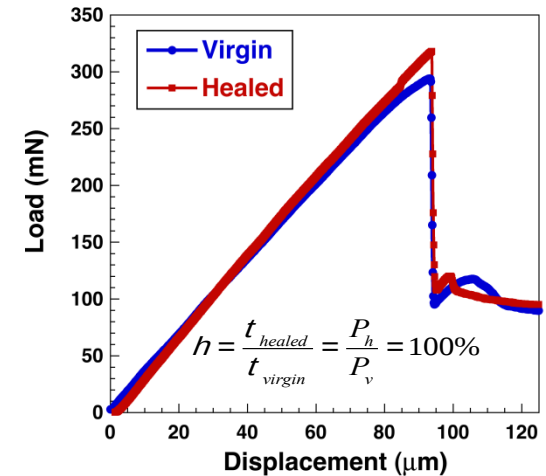
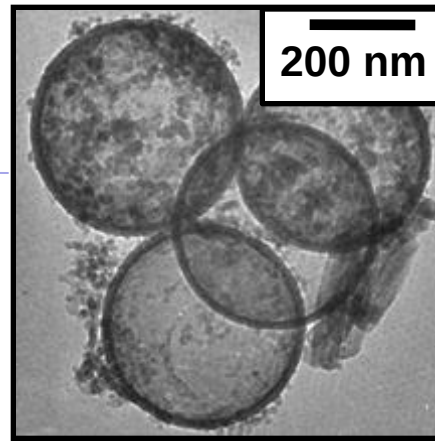


Functionalized glass fiber

EPA solvent + EPON 862 resin healing chemistry



TEM image of nanocapsules



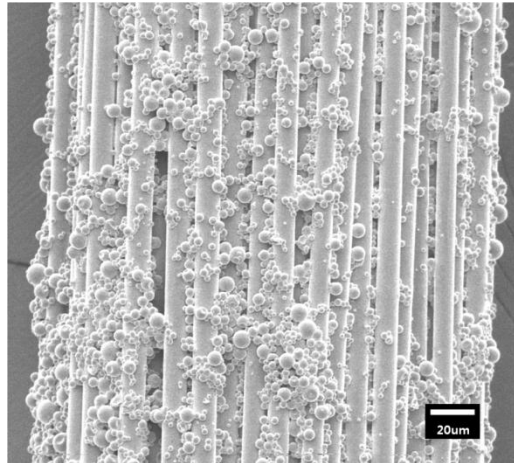
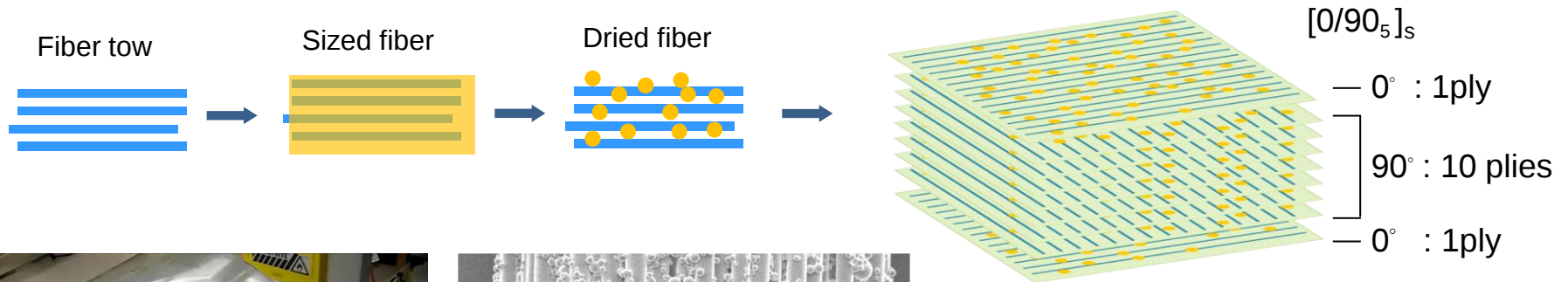
- **Full recovery of interfacial adhesion** is observed for **glass fibers** with the capsules of EPA solvent + EPON 862 resin outperforming DCPD/Grubbs system.



INTERFACIAL SELF-HEALING IN COMPOSITES (*UIUC: Sottos*)



- Successfully processed the 1st self-healing prepreg in continuous production mode



SEM image of E-glass fiber tow (200 count) with 3.3 μm diameter PU/UF microcapsules

E-glass fiber/epoxy resin

Matrix: EPON862/EPIKURE3274

Microcapsules

Core: 97:3 EPA(solvent)/EPON862

Shell: Polyurethane/polyUF shell

Proposed:

STTR (incl. Phase III) program covering multidisciplinary research on “self-healing composites” and involving the academia, AFRL and industry

- Cross-ply laminates of self-healing composite with well dispersed microcapsules were fabricated from prepreg.



STRUCTURAL REMODELING (UIUC: White/Moore) - Update



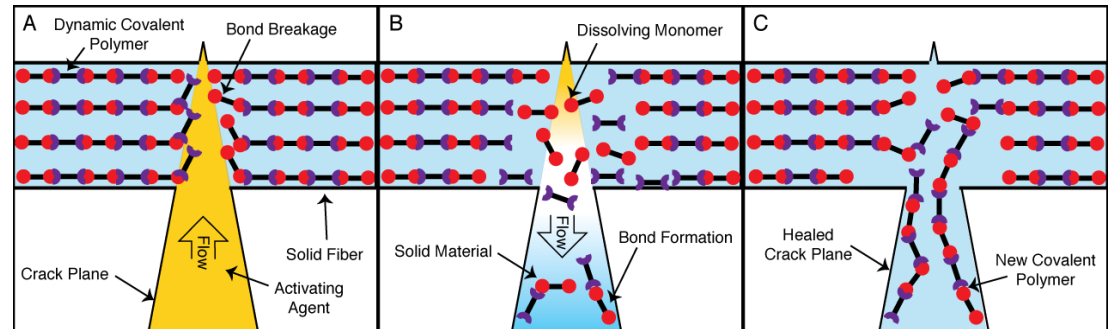
Regeneration in Nature:

Tree skink
lizard



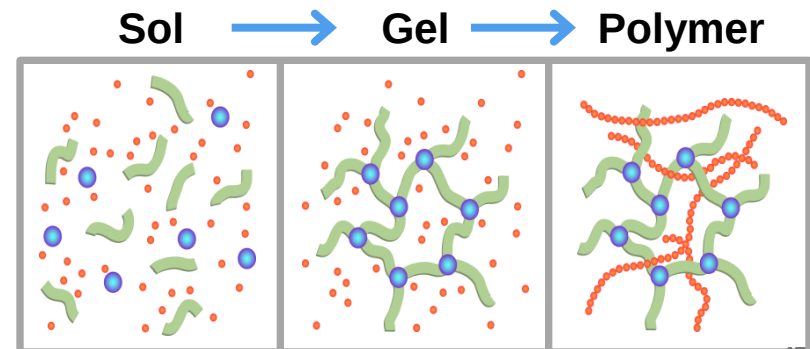
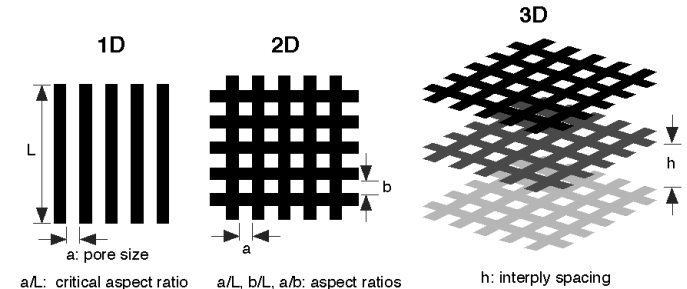
Linckia
starfish

Approach: Dynamic Polymers + Inert Scaffolds



Accomplishments:

- Synthesis of dynamic polymers which undergo stimuli-responsive (de)polymerization via **reversible covalent bonds** (i.e. liquid to solid and vice versa).
- Systematic study of structure-property relationships for dynamic polymers based on **ionic bonds** that are generally stronger and widely used in biological systems such as sacrificial bonds and proteins.
- A new class of material called **ionic molecular glass** which form a rigid network of ionic bonds below T_g .
- Developed novel **bi-stage chemistry** for regeneration allowing independent temporal control of **sol-gel** and **gel-polymer** transitions





SELF-COOLING COMPOSITES

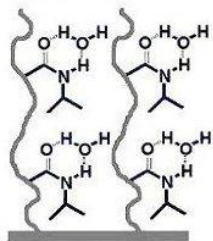
(Brown U: Xu)



Phase Changing Polymer - Poly(N-isopropylacrylamide) (PNIPAM)

- ❖ When heated in water above Lower Critical Solution Temperature (LCST) of $\sim 32^\circ\text{C}$, it undergoes a reversible phase transition from a **swollen hydrated state** to a **shrunk dehydrated state**, losing $\sim 90\%$ of volume.
- ❖ Melting point depends on molecular weight: 96°C for molecular weight of 20,000.
- ❖ Signature of polymer phase-change is still seen at $\sim 32^\circ\text{C}$ with high heating rate for **CNT reinforced composites** with PNIPAM matrices.

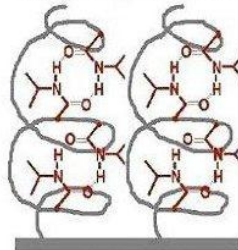
25°C
Hydrophilic



<LCST

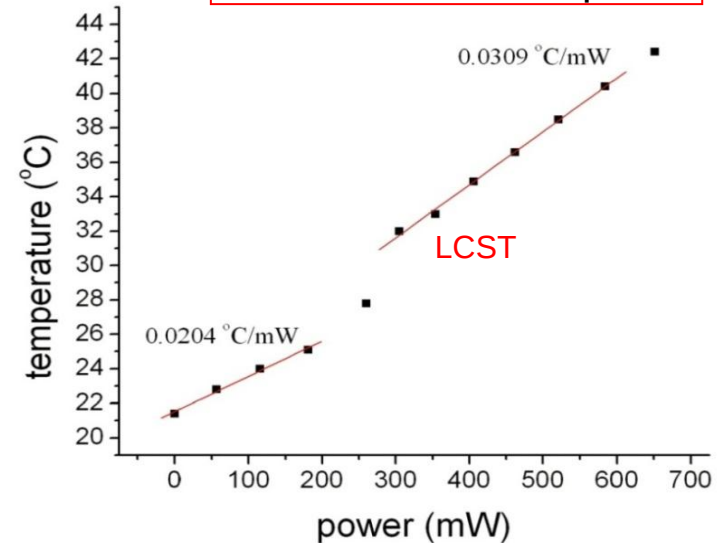
Heating up
Cooling down

40°C
Hydrophobic



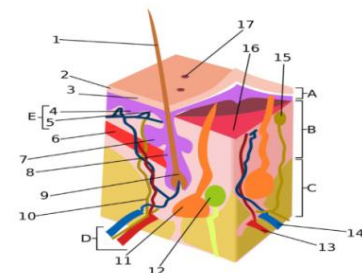
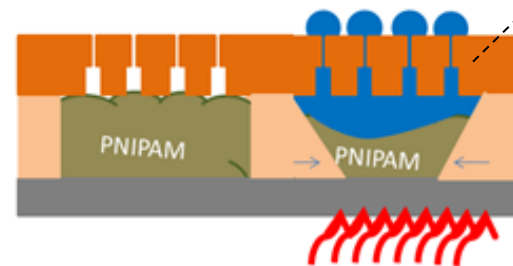
>LCST

CNT-PNIPAM composite



Proposed: Synthetic skin for self-regulated cooling ('sweating') leading to thermal signature reduction

Porous Al_2O_3 Membrane





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[^] **YIP**; * **MURI**; + **STTR**



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➤ **Design**

➤ **Design**

Fundamental

Life Prediction

Sensing, D

Self-Healing

Self-Cooling

Energy Transfer

Actuation,

Engineering

Subject:

**<< Nanocomposites for Sensing & Actuation
EM Tunable Fluids & Reconfigurable Antennas**

Shear Pressed CNT Sheets for Strain Sensing

**>> Self-Diagnostic Adhesive for Bonded Joints
Damage Detection w Time Domain Reflectometry
Bio-inspired Intelligent Sensing Materials**

**Embedded Sensors & Actuators for MAV
>> Load-Bearing Antennas of Conductive Textiles**

>> New; << Concluded

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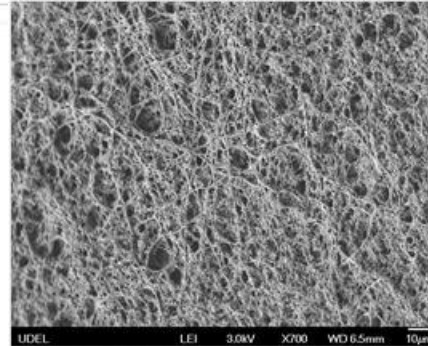
YIP'09 - NANOCOMPOSITES FOR SENSING (U Del: Thostenson)



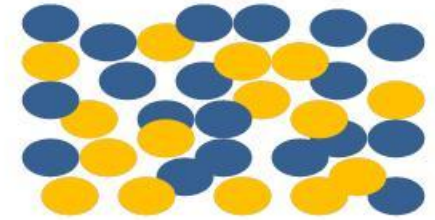
Parallel Co-Electrospinning of Different Materials

Polymer + Nanotubes

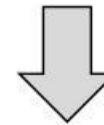
Neat Polymer



Porous Nanofiber Assembly



Co-Mingled Cross-Section



Secondary Processing

Consolidated Nanocomposite Film with Controlled Phase Separation



Hierarchical Nanocomposite Cross-Section

Co-mingled Nanofibrous Films

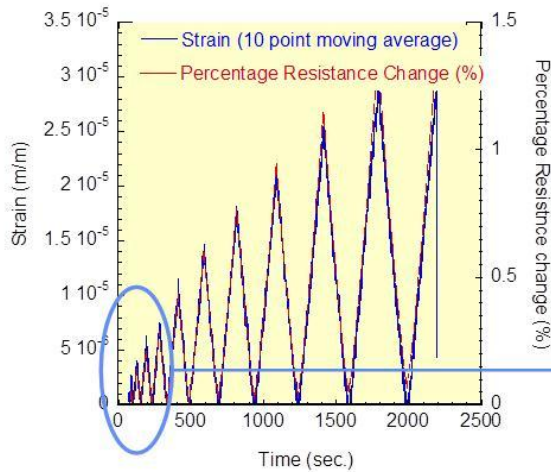
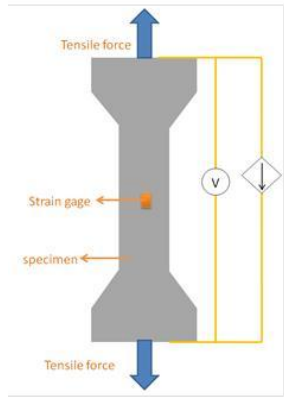
- Entanglement of the **electrospun jets** in the instability region can result in a uniformly co-mingled film of fibers where nanotubes are confined within individual filaments.
- Secondary-processing of co-mingled micro/nanofiber assemblies in a dense film results in a **self-reinforced hierarchical composite** with active polymer matrix.

Breakthrough in Composites Processing

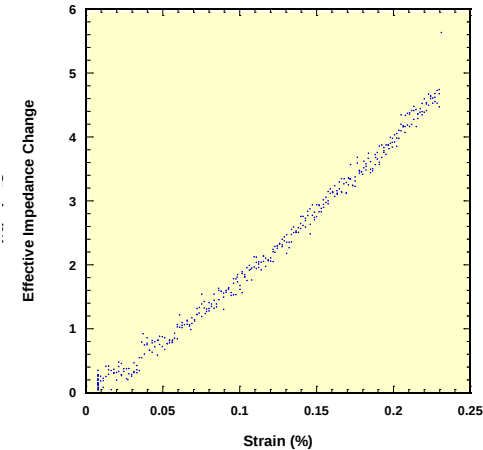
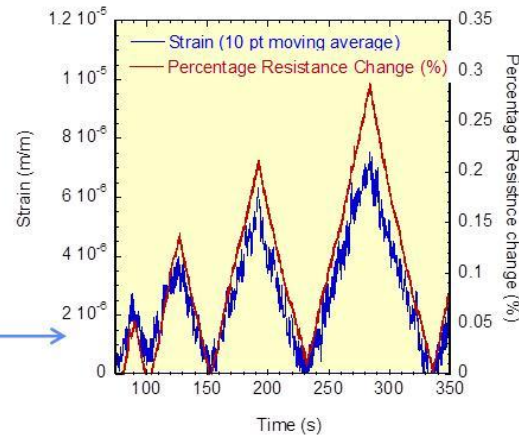
- Rapid consolidation of thermoplastics
- Greater control over morphology of nano-reinforcement at high concentration



YIP'09 - NANOCOMPOSITES FOR SENSING (U Del: Thostenson)



Very low strains



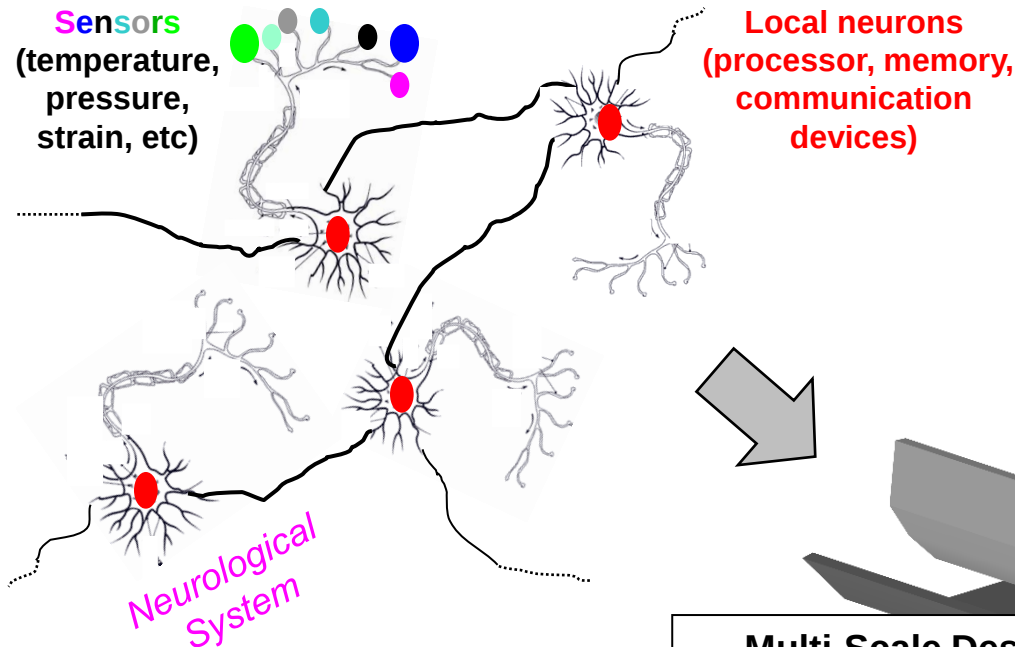
CNT (0.001) - PVDF

Accomplishments:

- The **electromechanical** response of **piezoelectric nanocomposites** is established at **high frequencies** utilizing a time-domain reflectometry approach.
- The integration of small quantities of carbon nanotubes impart apparent dielectrorestrictive response and capability for **non-contact strain sensing**.
- High-frequency **effective impedance changes** are directly related to changes in **dielectric** properties associated with **strain**
- Alteration of the **percolating network** can result in significant changes to the **resistance-strain behavior** in films and foams of nanocomposites.

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**.

Multi-Scale Design, Synthesis & Fabrication

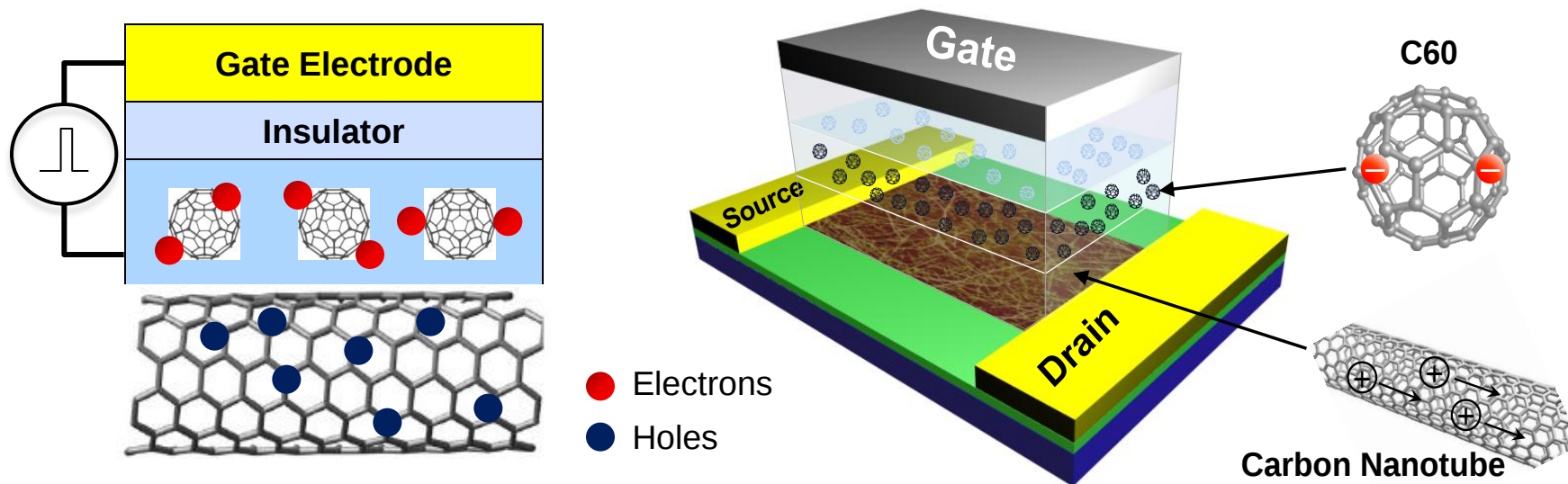
Bio-inspired Sensor Network

Stretchable Matrix

Synaptic Circuits

Autonomous System

EMULATING BIOLOGICAL SYNAPSE (UCLA: Chen) - Update



- The 2nd generation device emulating a **biological synapse**, which integrates spatiotemporal logic, memory and learning functions, has been developed by integrating **CNT's** and **C60-doped polymer** layer in a **field-effect transistor**. This novel “**synapstor**” offers drastically reduced power consumption compared to Si CMOS transistors.
- A voltage pulse applied on the gate of a synaptic transistor triggers electronic charge/discharge in the C60 molecules in the polymer to generate **post-synaptic current (PSC)**.
- The amplitudes of the post-synaptic current can be **configured to analog states** quantitatively (ranging from 10^{-12} to 10^{-7} A) and **reversibly** by modifying the charge inside the C60 molecules with a series of gate pulses.
- Based on the extrapolations of the experimental data, the analog values could be distinguished and preserved for years, indicating the **long-term nonvolatile analog memory** of the synapstor.



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Jose Andrade (Caltech)*
Kaushik Bhattacharya (Caltech)*
Chiara Daraio (Caltech)*
Michael Ortiz (Caltech)*
Chris Lynch (UCLA)*
Greg Carman (UCLA)*
Naresh Thadhani (GA Tech)
Sarah Stewart (Harvard U)
John Borg (Marquette U)

*** CoE**



PORTFOLIO OVERVIEW



NAME: B. A.

BRIEF DES

Basic science
into future

LIST OF SU

➤ Design

➤ Design

Fundamen

Life Predict

Sensing, D

Self-Healin

Self-Coolin

Energy Tra

Actuation,

Engineered

Subject:

- << **Multi-scale Simulation of Interfacial Phenomena**
- << **Deformation & Fracture of Silicon for MEMS**
- >> **3D Printed Composites for Topology Transform**

High-rate Physics of Heterogeneous Materials

Dynamic High-Pressure Behavior of Geomaterials

>> **New**; << **Concluded**

PI's & Co-PI's:

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Sarah Stewart (Harvard U)
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*** CoE**



AFOSR/RW CoE'12 - SHOCK PHYSICS (Caltech/UCLA: Ravichandran)

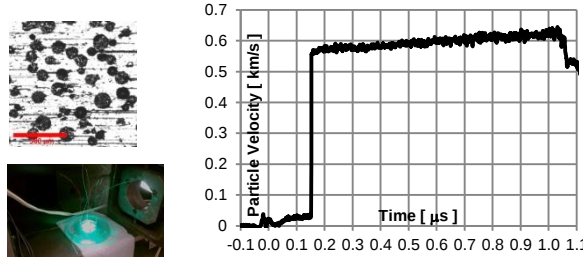


Objectives:

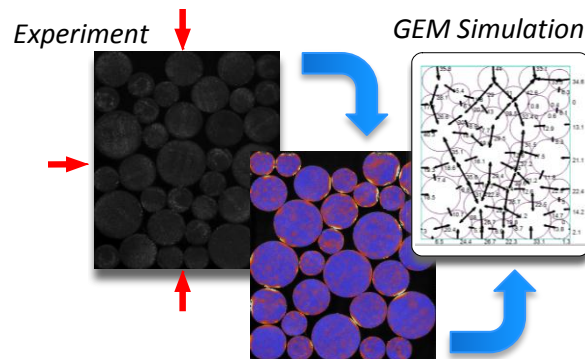
- Fundamental understanding of the **physics** of heterogeneous materials at **high-strain-rates** (10^5 - 10^7 /s) and **high-pressures** (1-100 GPa)
- Development of **microstructures** and **functional nanomaterials** for mitigating shock and damage
- Use of innovative methods for **educating and training** the next generation of scientists and practitioners

Achievements:

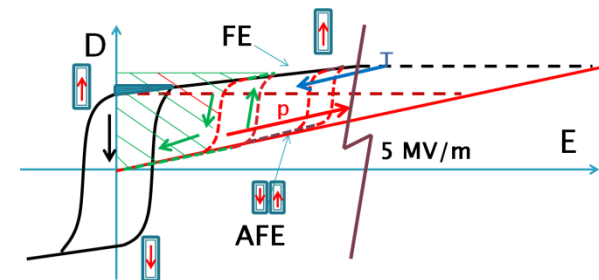
- Shock physics of “**model**” **particulate composite** (glass spheres embedded in PMMA).



- Concept of **metaconcrete** with **effective “negative” mass** which can potentially trap or disperse waves generated by shock loading
- Validated Granular Element Method (**GEM**) for computing interparticle forces in a model particulate material



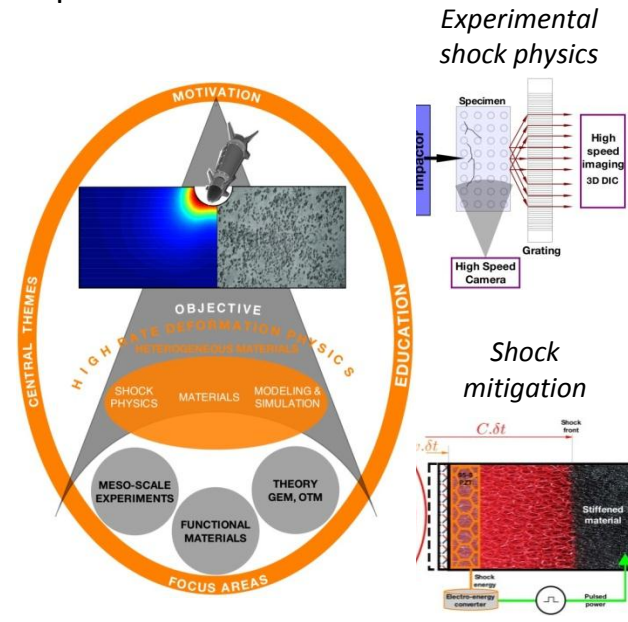
- Ferroelectric and ferromagnetic based **energy harvesting materials** for shock mitigation
- Pressure induced depolarization in 95/5 and 52/48 PZT based compositions characterized under hydrostatic and dynamic loading (split Hopkinson bar)



Shock energy corresponding to area to left of the curve can be harvested for ferroelectrics (Similar cycle for ferromagnetics)

Perspectives:

- New generation of analysis, design, simulation and experimental tools for heterogeneous material structures and systems of interest to the Air Force
- Design of robust munitions systems with novel protective systems for structures, electronics and guidance systems



Objective:

To develop a comprehensive **3D multi-physics**, **multi-scale** computational analysis and simulation capability for **multi-functional composite** structures.

Approaches:

1. Ubiquitous Multi-Physics Modeling incl. Transients:

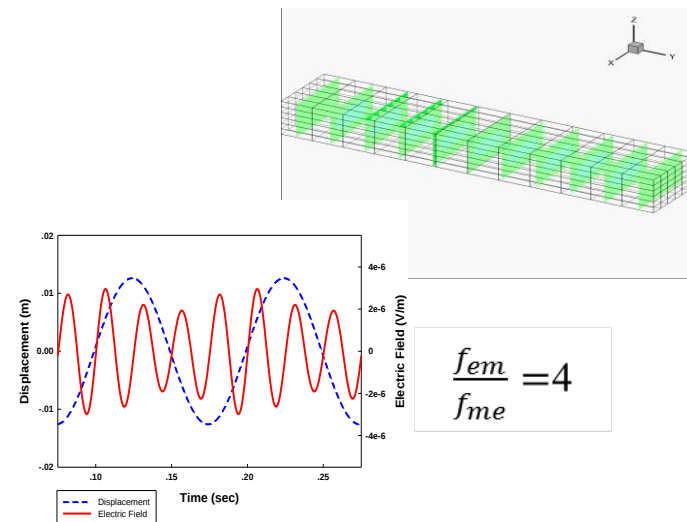
Coupled transient **electromagnetic** (EM) and dynamic **mechanical** (ME) fields

2. Temporal Multi-Scaling for Disparate Frequencies:

Electromagnetics (**ultrasonic frequency**) and mechanical vibration (**moderate frequency**) in a unified modeling framework

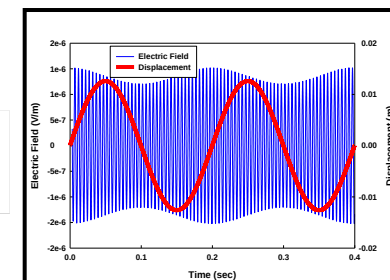
3. Spatial Multi-Scaling for Composite Media: Need to account for microstructure-structure interaction and design, e.g. conductors/reinforcements in antenna, conductor-substrate in sensors, and nodes (**piezoelectric sensor**) and wires (**connection of nodes**) in sensor network.

4. Piezoelectric Materials: Undergoing finite deformation



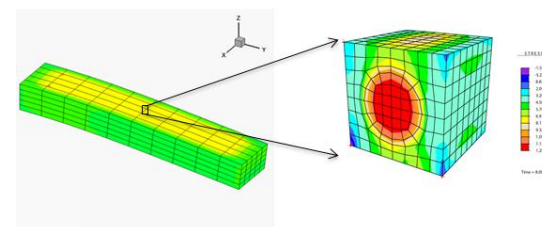
$$\frac{f_{em}}{f_{me}} = 4$$

$$\frac{f_{em}}{f_{me}} = 40$$



Macroscopic model

Microscopic model





SUMMARY



- The program is fully focused on the **multi-functional design** of advanced aerospace materials and structures.
- A major progress has been made in pursuing a new **vision** for **autonomic, self-sustaining** and **reconfigurable systems** and providing **basic research** support for mechanics of emerging materials and micro-devices as its foundation.
- Multi-disciplinary research bases are successfully formed for **“self-healing,” “structurally integrated energy harvest/storage capabilities,” “load-bearing antennas”** and **“morphing materials.”**
- Three initiatives are in progress for **“neurological system inspired sensory network”** (MURI '09), **“high-rate deformation”** (CoE'12) and **“biomolecular autonomic material systems”** (BRI'12).
- New initiatives are planned for **“muscular-skeletal system inspired actuation network”** and **“structural regeneration and remodeling”** in collaboration with AFOSR/AFRL-TD/NSF colleagues.