Genomics of Multifunctional Structures and Materials for Flight

Daniel J. Inman, Ph.D., Chair
Kelly Johnson Collegiate Professor
Department of Aerospace Engineering
The University of Michigan

e-mail daninman@umich.edu

Outline

- Definitions and History
- The concept
- Components of a flight structure
- A couple of examples
An Early Case for Multifunctional Thinking

“Another thing that kept us from going ahead faster was the belief that engines and air frames are separate entities. A review of aircraft design clearly shows how much time and cost were consumed in trying to fit existing engines into air frames that were never designed for each other. The two are, after all, a unit, and—with the advent now of vertical flying—air-flow requirements around a wing from the jet engine gas generator source make the wing construction an intimate part of the power plant.”

American Planes: The Lessons of History
by Grover Loening 1959
Smart Materials and Structures

- Initially motivated by human performance
- Based on wanting a structural and/or material to behave like a biological system, responding to its environment.
- Ended up focusing on transducer materials and material systems integrated into structural systems and devices
  - PZT, SMA, EPA, MR Fluids, etc.
Multifunctional Materials and Structures

• Structures and materials with multiple properties

• A deeper level of integration of “smart” materials into structural forms

• Examples include
  – Load bearing antennas
  – Load bearing batteries
  – Vascular self healing materials

A Concept of a Multifunctional Structure

• The functions
  – Structural integrity
  – Sensing
  – Actuating
  – Energy Harvesting
  – Energy Storage
  – Telemetry
  – Computing

• Performance
  – Cooling
  – Self Healing
  – Damping
  – Monitoring
  – Dynamic Response
  – Static Response
Sample Multifunctional Composite

- **A. Flexible Solar Panel**
- **B. QP16N (Harvester, Sensor)**
- **C. Thinergy Thin Film Battery**
- **D. Printable Circuit Board (PCB)**
- **E. Fiberglass Substrate**
- **F. MFC (Actuator)**
- **G. Composite**
- **H. Epoxy DP 460, Kapton**

Dimensions:
- $L_1 = 25\text{mm}$
- $L_2 = 94.6\text{mm}$
- $L_3 = 110\text{mm}$
- $L_4 = 735\text{mm}$
Functionally Graded Hybrid Composites (AFOSR MURI)

Oxide ceramic (TBC)
Functionally graded ceramic (MAX)/SMA composite (GCMcC)
High temperature sensor
Fuzzy fiber sensor
Vascular polymer matrix composite (PMC)

TAM, UICU, AFRL
U Mich, VT, UDRI
Stanford
Example 1: Multifunctional Spars

• Consider a small UAV with a spar
• What impact could a multifunctional approach have on the UAV performance?
  – Energy harvesting to run small electronics
  – Integrated energy storage
  – Active gust control
  – Active damping
Multifunctionality Focused on Integrating Batteries into Structures

Thomas and Qidwai at the Naval Research Lab present the original work on “structure + power” systems for unmanned vehicle applications.

Structural Batteries in UAVs

- Conventional lithium polymer batteries are embedded into structural components to carry load.
- Fabricated structures are tested under mechanical loading to determine if batteries remain functional.

Structural Batteries in UUVs

*Figure 3:* Bottom view of a Modular SB Stiffener specimen before it is bonded with a thin laminate skin showing two Kokam cells wired (internally) in parallel (Left). Top view of a Modular SB Stiffener with Skin (Right).

(Thomas and Qidwai, JOM 2005)

(Qidwai *et al.*, SDM Conference 2009, Thomas *et al.*, ICCM 2009)
Multifunctionality focused on tensile testing

Researchers at UCLA have investigated the ability to embed novel thin-film lithium batteries into structural composites

- NanoEnergy® thin-film batteries from Front Edge Technologies are embedded into a carbon fiber composite and tested under tensile loading
- Charge/discharge testing shows no damage to the cells under loading

Multifunctionality Integrating Solar Harvesting/Battery into a Structural System

Researchers have investigated the concept of multifunctional solar harvesting/load bearing/energy storage structures

- Thin-film solar panel integrated into CF composite
- Tested under tensile loading

(Maung et al, Solar Energy 2010)

- Thin-film solar panel bonded to flexible lithium polymer battery

(Kim et al, Comp Sci & Tech 2009)

- Thin-film solar panel combined with thin-film battery
- Device tested under tensile loading

(Dennler et al, Solar Energy 2007)
Self-Charging Structure Concept

Integration of piezoelectric material and a thin film battery

- **Self-Charging**
  - Novel thin-film batteries
  - Battery is part of structure
  - Piezo layers charge batteries

- **Load-Bearing**
  - Integrate harvester into design of host structure
  - Flexible batteries allow load bearing capability
  - Eliminate existing components

---

Energy Flow

\[ P_1(t), P_2(t), \ldots, P_n(t) \]

\[ F(x,t) \]

**Integration of piezoelectric material and a thin film battery**


* U.S. Patent Application No. 61/158,568 (Anton, Erturk, Inman)
Electromechanical Modeling of Wing Spar

The assumed modes method is used to model the cantilever energy harvesting wing spar. The model developed here is based on the experimentally validated assumed modes model*

- Base excitation problem
- Forward and backward piezoelectric coupling
- Non-uniform material properties along $x$
- Lumped mass at arbitrary point “$L_4$” representing embedded sensor node

Self Charging Wing Spar for UAV Applications

- Flexible solar panels
- Piezoelectric transducer

- 70 mW
- 30 mW/g²

Thin film Battery
E/M CHARACTERIZATION: of the multifunctional system for different vibration, and solar energy levels.

**Different stages of fabrication**

- **Aluminum (innermost)**
- **Piezo layer**
- **Thin-film battery**
- **Flexible solar panel (outermost)**

**Assembly:** 4” x 1” x 0.06”

**Solar power (outdoor)**

**Vibration power at resonance**

**Power [mW]**

**Power [mW/g^2]**

**Load resistance [ohms]**

**Load resistance [ohms]**

**Circuitry**
Modeling via assumed modes approach and then experimentally validated

Peak Power Output

- **Short Circuit**
  - 2.68 mW/g (model)
  - 2.67 mW/g (exp)

- **Open Circuit**
  - 2.70 mW/g (model)
  - 3.05 mW/g (exp)
Experimental Testing and Model Validation

- 30 modes are used in the Rayleigh-Ritz formulation to achieve convergence.
Strength analysis of the composite system was analyzed

- The assumed modes electromechanical model employed previously can be used to describe the stress in a specific layer under dynamic excitation.
- 3 Point bending tests performed
- PZT the weakest element
Is there an effect in terms of flight time for a multifunctional spar?

The model given by Thomas et al. is based on simple aerodynamic relations and energy relations.

\[
PR = T_R V_\infty
\]

Thrust, Drag, Lift, Weight

\[
T = D
L = W
T_R = \frac{W}{L/D}
\]

Power Required for Steady, Level Flight

\[
PR = \frac{W}{C_L/C_D} V_\infty
\]

Power Required

\[
V_\infty = \sqrt{\frac{2W}{\rho_\infty S C_L}}
\]

Definition of Lift

\[
L = W = \frac{1}{2} \rho_\infty V_\infty^2 S C_L
\]

\[
PR = \sqrt{\frac{2W^3 C_L^2}{\rho_\infty S C_D^3}}
\]

\[
PR \quad \text{Power Required}
T_R \quad \text{Thrust Required}
V_\infty \quad \text{Aircraft Velocity}
T \quad \text{Thrust}
D \quad \text{Drag}
L \quad \text{Lift}
W \quad \text{Weight}
C_L \quad \text{Lift Coefficient}
C_D \quad \text{Drag Coefficient}
\rho_\infty \quad \text{Air Density}
S \quad \text{Wing area}

\text{AEROSPACE ENGINEERING}

\text{UNIVERSITY of MICHIGAN • COLLEGE of ENGINEERING}
Energy Expressions

The power required for flight has been derived. The flight endurance depends on the total energy available and the power required for flight.

Power Required

\[
P_R = \sqrt{\frac{2W^3C^2_D}{\rho_\infty SC_L^3}}
\]

Energy Balance

\[
\text{Power} = \frac{\text{Energy}}{\text{Time}} \Rightarrow \text{Time} = \frac{\text{Energy}}{\text{Power}}
\]

Flight Endurance Including Harvesting

\[
t_E = \frac{E_{\text{avail}}}{P_R} = \frac{E_B\eta_B + P_{\text{Harv}}t_E}{\sqrt{\frac{2W^3C^2_D}{\rho_\infty SC_L^3}}/\eta_P} = \frac{E_B\eta_B + P_{\text{Harv}}t_E}{W^{3/2}} \left(\frac{\rho_\infty SC_L^3}{2C_D^2}\right)^{1/2} \eta_P
\]

\[
t_E = \frac{E_B\eta_B}{W^{3/2} - P_{\text{Harv}} \left(\frac{\rho_\infty SC_L^3}{2C_D^2}\right)^{1/2} \eta_P} \left(\frac{\rho_\infty SC_L^3}{2C_D^2}\right)^{1/2} \eta_P
\]

- \(t_E\): Flight Endurance
- \(E_{\text{avail}}\): Available Energy
- \(E_B\): Battery Energy
- \(\eta_B\): Battery Efficiency Factor
- \(P_{\text{Harv}}\): Harvester Power
- \(\eta_P\): Propeller Efficiency

Steve Anton, Tennessee Tech
In order not to provide a weight/flight time penalty the added system must show some improvement

• If a multifunctional spar can be made with the same weight as the original spar (requiring the removed mass to have the same strength)
  – This would be a productive solution to UAV sensing
  – Not likely from looking at our strength studies
• If the multifunctional spar can be reduced in strength without sacrificing performance
  – A reduction in strength can be tolerated if it was overdesigned
  – Or if a control system can be added to circumvent the need for over design
• Next we look at adding a control system for gust alleviation
  – Requires search for minimum energy controllers
Modeling Results for the Multifunctional Spar

Wing Spar Modal Frequency Prediction

<table>
<thead>
<tr>
<th>Beam(\text{Hz})</th>
<th>1(^{st})</th>
<th>2(^{nd})</th>
<th>3(^{rd})</th>
<th>4(^{th})</th>
<th>5(^{th})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Euler beam</td>
<td>10</td>
<td>63</td>
<td>175</td>
<td>344</td>
<td>568</td>
</tr>
<tr>
<td>Multi-Function Beam(^{1}) (Analytical)</td>
<td>12.0</td>
<td>75.0</td>
<td>210</td>
<td>411</td>
<td>680</td>
</tr>
<tr>
<td>Multi-Function Beam(^{2}) (Analytical)</td>
<td>11.7</td>
<td>73.2</td>
<td>205</td>
<td>402</td>
<td>664</td>
</tr>
<tr>
<td>Multi-Function Beam(^{1}) (FEM)</td>
<td>13.3</td>
<td>75.7</td>
<td>211</td>
<td>410</td>
<td>685</td>
</tr>
<tr>
<td>Multi-Function Beam(^{2}) (FEM)</td>
<td>12.9</td>
<td>74.1</td>
<td>207</td>
<td>403</td>
<td>673</td>
</tr>
</tbody>
</table>

\(^{1}\): rule of mixtures
\(^{2}\): cross section transformation
Multifunctional Spar for Gust Alleviation in UAVs

- Because they are small and lightweight wind gusts can severely the flight control of a UAV
- Here we propose a multifunctional wing spare that contains harvesting from flow, storage, controller and sensing
- Components include
  - A minimum energy controller
  - And the components listed in the figure below

Our eventual Goal: here are the components needed
The first task is to minimize the amount of energy required to perform control

- Which type of PZT actuation uses the least amount of power?
- Which type of PZT makes the best sensor
- Which type of PZT makes the best harvester
- Which control law uses the least amount of power to achieve the same performance
Macro Fiber Composites, an Actuation Enabler (MASA)

- Electrode printed on Kapton base
- Fibers diced out of sheets of PZT
- Alignment of top electrode
- Heat and pressure cure cycle, then PZT poling

W. K. Wilkie et al
Actuation Characteristics for Unimorph Cantilever Beams

Note: the length scales have a linear effect on the actual strain output, therefore the mass normalization results a fair comparison of four actuators with variation in area and ceramic thickness.

Summary: MFC 8528-P1 largest actuation ability @12 Hz excitation frequency. Due to largest electromechanical coupling, largest actuation voltage allowance (-500V+1500V), lowest capacitance.

Electromechanical Coupling Coefficient:

\[ k^2 = \frac{\alpha_s^2}{C_p (K_p + K_s)} + \frac{\alpha_c^2}{C_p (K_p + K_s)} \]
Sensing Characteristics for unimorph cantilever beam control

**Note:** the mass normalization: a fair comparison with variation in ceramic thickness and area

**Summary:** MFC 8528-P1: highest sensing ability, Optimal Load 495k ohms @ various voltage excitation around 12Hz
Feed back control methods with a switching algorithm over the top:

When \( u(t) > 0 \)

if \( u(t) < V_{ext} \), then connect to point 1, the input voltage \( u = u(t) \)

if \( u(t) \geq V_{ext} \), then connect to point 2, the input voltage \( u = V_{ext} \)

When \( u(t) < 0 \)

if \( u(t) \leq V_{ext} \), then connect to point 2, the input voltage \( u = V_{ext} \)

if \( u(t) > V_{ext} \), then connect to point 1, the input voltage \( u = u(t) \)
Power Consumption Greatly Drops Using a Saturation Control

Several common control laws are compared, each with the same initial conditions and the same peak and settling time:

| Table 1 Power Consumption of Different Controllers for Free Vibration Suppression |
|---------------------------------|----------------|----------------|----------------|----------------|----------------|
|                                 | Open Loop     | PPF            | Nonlinear      | Bang-bang-PPF  | Bang-bang-Nonlinear |
| Initial Values (mm, mm/s)       | (4,0)         | (4,0)          | (4,0)          | (4,0)          | (4,0)          |
| Settling Time $T_s$ (s)          | 9.40          | 4.00           | 4.00           | 4.08           | 4.08           |
| Average Power (mW)              | 0             | 0.157          | 0.164          | 0.0917         | 0.0920         |
Why does the on off controller reduce total power consumption?

In a continuous controller most of the energy is expended in the first two periods. The saturation controller clips this
Voltage-dependent Electromechanical Coupling

Fundamental Modal Response:

\[ \ddot{h}_1(t) + 2 \lambda_1 \dot{h}_1(t) + \Delta_1 h_1(t) = bu(t) \]

Coupling Coefficient:

\[ b(u) = -Y_{p} d_{33}(u) \frac{h_{1}[(h_{r} - \alpha h_{p})^{2} - (h_{r} + \alpha h_{p})^{2}]}{2r_{0} + r_{c}} \Gamma_{1} \]

\[ \Gamma = \sum_{i=1}^{N_i} \left( \frac{\phi_1(x_{i0}) - \phi_1(x_{i1})}{x_{i0} - x_{i1}} + \frac{\phi_1(x_{i2}) - \phi_1(x_{i3})}{x_{i3} - x_{i2}} + \frac{d\phi_1(x)}{dx} \right)_{x_{i0}} \]

\[ b(u) = a_f e^{b_f u} + c_f e^{d_f u} \]
Fundamental Modal Response:

\[ \ddot{h}_1(t) + 2 \dot{h}_1(t) + 2h_1(t) = bu(t) \]

To account for this voltage-dependent electromechanical coupling coefficient in real time, an corresponding adaptive algorithm is developed correspondingly.

Coupling Coefficient:

\[ b(u) = -Y_p d_{33}(u) \frac{h_i[(h_d - \alpha h_p)^2 - (h_e + \alpha h_p)^2]}{2r_a + r_e} \Gamma_i \]

Voltage-dependent Electromechanical Coupling

Adaptive Control for Voltage-dependent behavior Compensation

**Diagram:**

- **GA:** Adaptive Algorithm
- **Adj:** Adjustment
- **GP:** Active/Hybrid Controller
- **H:** Beam w/ MFC
- **u(t):** Input
- **x(t):** Output
Adaptive Control for Voltage-dependent behavior Compensation

PPF

Nonlinear Switching PPF
GUST ALLEVIATION FOR A MULTIFUNCTIONAL WING SPAR USING MINIMUM CONTROL POWER VIA PIEZOCERAMICS AND HARVESTED ENERGY

Gust Signal 1

\[ \Phi_{Dry}(\omega) = \frac{\sigma_v^2 L_v}{\pi U_0} \frac{1 + 3\left(\frac{L_v \omega}{U_0}\right)^2}{\left(1 + \left(\frac{L_v \omega}{U_0}\right)^2 \right)^2} \]

Dryden Power Spectrum Density (PSD):

\[ K_v = \sqrt{\frac{3\sigma_v^2}{\pi U_0 L_v}}, \quad G_v(s) = \frac{s + \frac{U_0}{\sqrt{3L_v}}}{(s + \frac{U_0}{L_v})^2} \]

Filter Transfer Function:

\[ U_0 : \text{the aircraft trim velocity} \]

\[ L_w : \text{the scale of turbulence} \]

\[ \sigma_w : \text{the RMS vertical gust velocity} \]
GUST ALLEVIATION FOR A MULTIFUNCTIONAL WING SPAR USING MINIMUM CONTROL POWER VIA PIEZOCERAMICS
THE GUST IS MODELED AS FOLLOWS:

$U_0$ : the aircraft trim velocity

$L_w$ : the scale of turbulence

$\sigma_w$ : the RMS vertical gust velocity
GUST SIGNAL RESPONSES ON MULTIFUNCTIONAL WING SPAR

Gust Responses on Multifunctional Wing Spar

\[ \begin{align*}
    n(t) & \xrightarrow{K_v} \text{Lowpass Filter } G_v(s) \\
    & \xrightarrow{\frac{1}{0.3s+1}} \text{Delay of Wg3} \\
    & \xrightarrow{\frac{1}{0.15s+1}} \text{Delay of Wg2} \\
    & \xrightarrow{Wg1(t)} \text{State Space Representation of Multifunctional Wing Spar} \\
    & \xrightarrow{x' = Ax + Bu} \text{Multi-Mode Operation} \\
    & \xrightarrow{\text{Gain } K_v} \text{Gust Response } \text{OL} \\
    & \xrightarrow{\text{To Workspace}} \text{Gust Time Response}
\end{align*} \]

Wing Spar Modal Frequency and Damping Predictions

<table>
<thead>
<tr>
<th></th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequencies(\text{Hz})</td>
<td>10</td>
<td>72</td>
<td>207</td>
<td>403</td>
<td>673</td>
</tr>
<tr>
<td>Damping</td>
<td>0.01</td>
<td>0.05</td>
<td>0.2</td>
<td>0.3</td>
<td>0.5</td>
</tr>
</tbody>
</table>
OPEN LOOP RESPONSE AND CLOSED LOOP RESPONSE SHOWING THAT THEORY PREDICTS THE CONCEPT SHOULD BE SUCCESSFUL

Harvest for 40 s to control a 1 sec gust
Does it work?

- For any wind gust duration $t_g >$ settling time $t_s > 0.8s$, the total control energy satisfy:

$$E_{tot} = E_{tr} + P_{st} \times (t_g - t_s).$$

- Then the total control energy required by PSF and REC becomes:

$$E^{PSF}_{tot} = 6.6 + 1.2 \times (t_g - 0.8).$$

$$E^{REC}_{tot} = 1.6 + 1.0 \times (t_g - 0.8).$$

- For average harvested power $P_{hav}$, the required harvesting time $t_h$ to control a wind gust of duration $t_g$ yields:

$$t_h = \frac{E_{tot}}{P_{hav}}.$$ 

Reduced a relative tip displacement due to cloud wind gust disturbance by 14dB for Mode 1 and 12dB for Mode 2, using vibration energy harvested during a period of time at least 40 times longer than the wind gust duration.
Example 2: Electronic Damping

• Damping in aero structures is critical from skins to engine blades
• One difficulty with damping materials is that their effectiveness falls off with frequency and temperature
• One answer might be to incorporate and integrated control system to compensate for temperature and frequency variations

Ya Wang, University of Michigan
Temperature Dependence of Viscoelastic Materials

Viscoelastic treatment

-65 -55 -45 -35 -25 -15 50 60 70 80 90

Frequency

dB

Plain - horiz
25 C
35 C
45 C
55 C
Embedded Controller Keeping the Settling Time Fixed as Temperature and Frequency Vary

\[ u(t) = V_{ext} \]

\[ u(t) > V_{ext} \]

\[ t_s > T_s \]

Disturbance/load

NO

Composite structure

NO

Controller

YES

NO

YES

Embedded Controller Keeping the Settling Time Fixed as Temperature and Frequency Vary

\[ u(t) = V_{ext} \]

\[ u(t) > V_{ext} \]

\[ t_s > T_s \]

Disturbance/load

NO

Composite structure

NO

Controller

YES

NO

YES
Advances in flexible electronics (inorganic)

• Inorganic Flexible or Printable Electronics are receiving increasing development and research
  – Based on Thin Film Transistors (TFT)
  – Substrates are plastic, silicon wafers, polyimides, glass and others
  – Most research focuses on manufacturing and use of very simple electronics (not complete circuits)

• Mechanical Characterization is in its infancy
  – Only simple bending test with strain measurements are available plotted against some metric of electrical performance
  – No dynamic tests
  – Not much mechanics analysis
Advances in flexible electronics (organic)

- Organic electronics is tied to the development of wearable computing, sensing, and electronics.
- Organic materials include sublimed and solution-processed semiconductors such as:
  - Pentacene
  - Pligothiophenes
  - Hexadecafluorocopper phthalocyanine
  - Polythipphene
  - And others I cannot pronounce or spell correctly.
- Applications are displays and RF tags.
- Mechanics analysis, fatigue, etc., is in its infancy.
- Not much on mechanics of electronics integrated into structures.

Example 3: Morphing Aero Surfaces

- *Configuration Morphing*: Changing the wing from one mission optimal to another
  - Motivated by a hawk
  - Long straight wings for gliding
  - Short delta wings for fighting

- *Maneuvering Morphing*: Changing the wing for flight control and performance improvement
  - Wing twist
  - Camber changes
  - Reflex changes
  - Drag rudders and spoilers
Active Composite Morphing Surfaces for Small UAVs

• Morphing refers to shape changing
• Applied to aircraft it can be used to
  – Create an plane that is able to fly in multiple configurations such as both loiter and dash
  – Remove discrete control surfaces by using wing twist, asymmetric wing extension and chamber changes to create roll moments
  – Perching and flapping
• Morphing has the potential to drastically improve maneuverability.
MFC Thin Airfoil Design

Airfoil Designs Evaluated for Aerodynamic Characteristics using XFOIL

Onur Bilgen, Old Dominion University
Thick Airfoil: Morphing Airfoil with Box Internal Structure is Designed for Bi-directional Actuation

Design Features
- Circular or Elliptical Leading edge
- Bimorph top and bottom surfaces employing MFC actuators
- Substrate chosen for relatively high chordwise deflection output and spanwise rigidity

First Prototype for Benchtop Demonstration
- Trailing edge is 90 mm from the box structure
- 15mm deflection for max. positive actuation
- –18mm deflection for max. negative actuation
Demonstration of the Thick Airfoil Design in a Flow

(1) -1400V, c=-4.14, \( \alpha = -6.3 \)

(2) 0V, c=-1.2, \( \alpha = -2.53 \)

(3) 1400V, c=5.24, \( \alpha = 7.01 \)

(4) 1400V, c=5.48, \( \alpha = 6.9 \)

(5) 0V, c=2.17, \( \alpha = 2.16 \)

(6) -1400V, c=-3.98, \( \alpha = -6.18 \)
Some Examples of Conformal Aileron Control

- Articulated - Hydraulic actuated
  (Monner et al 1998)

- SMA, arch actuated:
  (Barbarino et al 2011)

- MFC (piezo) bimorph actuated
  (Butts et al 2010)

modified B.C. for larger actuation
(Bilgen et al 2010)

Alexander Pankonien
Spanwise Morphing Trailing Edge Concept

Eliminates aerodynamic losses from spanwise and chordwise discontinuities while adapting to maximize performance over a variety of flight conditions

Alexander Pankonien, University of Michigan
Development of Modular Section

• Goal:
  Develop scalable, reproducible spanwise section for experimental implementation

• Modular design:
  – Actuator
  – Inactive spanning skin

Actuator:
Modularized the Cascading Bimorph concept from Bilgen et al. 2010 to unimorphs for weight considerations
Development of Flexure Box for Actuator

• Replaced hinges with flexure joints, returning to solid-state device, eliminating hinge friction.

• Parametrically-controlled compliance with multimaterial 3D printer (Objet Connex 500)
  
  – Can print materials ranging in stiffness from rigid plastic to elastomer

• Tested effect of flexure height on actuation range
3D-Printed Skin for Compliance Tailoring

• Morphing skin requires: (Thill et al 2008)
  – Low in-plane stiffness
    to maximize actuator range, effect
  – High out of plane stiffness
    to minimized impact of aerodynamic loads

• Anisotropic skin designs include:
  – Bistable plates, (Lachenal et al 2012)
  – Composite skins, (Murugan et al 2011)
  – Corrugated Skins (Ghabazi et al 2012)
  – Cellular Honeycombs
    • Hexagonal Honeycombs (Olympio et al 2010)

• Current work uses 3D-printed elastomeric honeycomb pattern to tailor compliance
  – Mimicked sizing parameters of commercially-available aramid core honeycombs
So What?


• Compared this distributed morphing vs servo control and found significant positive differences in performance:
  – Heavier
  – Better lift-to-drag-ratio
  – Comparable power consumption
  – Increased band width by an order of magnitude

• Not a complete comparison but a positive start
Summary

• Multifunctional Structures have a way to go to prove their utility but history is on their side
• This sort of approach could lead to lighter higher performance structural systems
• One of the road blocks is embedded electronics: modeling and design
• The future for improved structures may well lie in sorting out integration of computing and power within a structural system
Acknowledgements


- AFRL (munitions) and AVID, LCC supported the early morphing projects.

- Kelly Johnson Professorship, University of Michigan.

- Students:
  - Alex Pankonien, Cassio Faria

- Former Students:
  - Dr. Steve Anton, Dr. Ya Wang, Dr. Onur Bilgen, Dr. John Ohanian.
Currently there is a rush to use biological terminology to describe engineering systems. This is a bit backwards as engineering is the more precise discipline. In modern molecular biology and genetics, the genome is the entirety of an organism's hereditary information. The complete set of genetic material of an organism, or as interpreted here — a complete set of information about a given structure. Here we invoke the term to look at multifunctional structures in the context of aerospace applications. Others invoke the term to look at the different scales of the structure.
The compensation designed around PPF also works for the other controllers.

Note: the function works successfully for PID, the nonlinear, the LQR and their hybrid control versions too.
Thin airfoil configuration and lift and drag coefficients vs angle of attach.