Some design principles of biomimetic actuators

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Mixed numerical and experimental methods applied to the mechanical characterization of bio-based materials

Thematic workshop

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Introduction: Biomimetics

**Discussion**

**Biomimetic materials research: what can we really learn from nature’s structural materials?**

Peter Fratzl*

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**We see the solution and need to find the problem which was solved**

**We know the problem and need a solution**
### Biological Material vs Engineering Material

**Few Chemical Elements** dominate:  
C, N, O, H, Ca, P, Si, S….

**Large Variety** of Elements:  
Fe, Cr, Ni, Al, Si, C, N, O, …

<table>
<thead>
<tr>
<th>Growth</th>
<th>Fabrication</th>
</tr>
</thead>
<tbody>
<tr>
<td>by biologically controlled self-assembly (approximate design)</td>
<td>from melts, powders, solutions, etc. (exact design)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hierarchical Structure</th>
<th>Form (of the part) and Micro-structure (of the material)</th>
</tr>
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<tbody>
<tr>
<td>at all size levels</td>
<td></td>
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<table>
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<tr>
<th>Adaptation</th>
<th>Design of the part and Selection of material according to function</th>
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<tbody>
<tr>
<td>of form and structure to the function</td>
<td></td>
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<thead>
<tr>
<th>Modeling and Remodeling: Capability of adaptation to changing environmental conditions.</th>
<th>Secure Design of the part and secure materials selection (considering possible maximum loads as well as fatigue)</th>
</tr>
</thead>
</table>

**Healing:**  
Capability of self-repair

[Fratzl - J. Roy. Soc. Int. 2007]
Pine cones: opening while drying

Swelling and shrinking of fibre-reinforced matrix polymers

Orientation of cellulose microfibrils in the scales of the pine cone

[Dawson et al. - Nature 2007]
Wheat awns: a humidity driven motor

[Elbaum et al. – Science 2007]
Microfibrils angle control swelling at the cell level

[Fratzl et al. – Faraday Discussions 2007]
Ice plant: A geometric-controlled opening

*top-view of dry capsule*

- Protective valve

*top-view of wet capsule*

- Hygroscopic keel

- Swelling of individual cells

[Harrington, M. – Guiducci, L. - Razghandi, K.]

Valve Cutaway
Side View Dry

Hygroscopic Keel

Hinge

Valve Cutaway
Side View Wet

[DRY] [1 µm] [1 µm] [WET]
Helical actuation of Erodium awns upon drying

[Rivka Elbaum, Yael Abraham, University of Jerusalem Israel]
General mechanical formulation

\[ x = \Phi(X) \]

\[ \varepsilon^* (X) \]

\[ \varepsilon = \varepsilon^{el} (x) + \varepsilon^* (x) \]

\[ \sigma = E : \varepsilon^{el} (x) \]
Bilayer Top-Down Analogy

Biological system

Simple model

Δ Relative humidity

Passive $\varepsilon=0$
Active $\varepsilon=1$

elastic material ($E$, $v$)

\[
\frac{1}{r} \propto \frac{\varepsilon}{h}
\]

[Davide Ruffoni, Thomas Antretter]

[Timoshenko - 1925]
Cuboid shapes
Cuboid partitions

Specify partitioning:
- Horizontal: 3
- Vertical: 2
- Longitudinal: 2

Options: OK, Cancel
Finite Element Model
Eigenstrain field

elastic material \((E=1, \nu=0.3)\)

Passive \(\varepsilon=0\)
Active \(\varepsilon=1\)

Graphical picking
Random assignment
Helical distribution
Controlling global actuation through material distribution

Active

Passive

Steps: 1; Load, Thermal loading of the beam
Increment: 2; Step Time = 1.000
Primary Var: THX, THX11
Deformed Var: U Deformation Scale Factor: 4.0e+00
Extrudable cross-sections

[An excursion into the design space of biomimetic architectured biphasic actuators
Restricting the space of actuation

R1 1M
(a)  

R4 0M
(b)  
(c)  
(d)  
(e)
Frameworks for eigenstrain actuation

Finite element model

\[ \sigma = E : \varepsilon^{el} = E : (\varepsilon - \varepsilon^*) \]

Point-Spring model

\[ f = -kx = -k(l - l_0) \]
Bending

\[ l_0 (1 + \varepsilon) = \varepsilon \]

\[ \varepsilon = 0.2 \]
Twisting

\[ l_0(1 + \varepsilon) \]

\[ \varepsilon = 0.2 \]
Curling = Bending + Twisting

\[
\begin{align*}
    l_0 (1 + \varepsilon_B) \\
    l_0 (1 + \varepsilon_T)
\end{align*}
\]

\[\varepsilon_B = 0.2 \mid \varepsilon_T = 0.2\]
Exploring parameter space

\[ \varepsilon_B = 0 \quad \varepsilon_B = 0.4 \quad \varepsilon_B = 0 \quad \varepsilon_B = 0.4 \quad \varepsilon_B = 0.6 \]

\[ \varepsilon_T = 0 \quad \varepsilon_T = 0 \quad \varepsilon_T = 0.4 \quad \varepsilon_T = 0.4 \quad \varepsilon_T = 0.2 \]
Space Curve

**Frenet-Serret Frame**

\[
\begin{align*}
\mathbf{t} &= \frac{d\mathbf{P}(s)}{ds} \\
\mathbf{n} &= \frac{1}{k} \frac{dt(s)}{ds} \\
\mathbf{b} &= \mathbf{t} \wedge \mathbf{n}
\end{align*}
\]

\[
\begin{align*}
\frac{d}{ds} \begin{pmatrix} t \\ n \\ b \end{pmatrix} &= \begin{pmatrix} -\tau \\ 0 \\ k \end{pmatrix} \wedge \begin{pmatrix} t \\ n \\ b \end{pmatrix}
\end{align*}
\]

**Curvature** \( k(s) \)

**Torsion** \( \tau(s) \)
Curvature

\[ k \]

\[ \varepsilon_B = 0 \]

\[ \tau = 0 \]
Torsion

\[ \tau = B \varepsilon_T \]

\[ \varepsilon_B = 0.1 \]
Coupling

\[ \varepsilon_B = 0.1 \]
Spatial functions

\[ \varepsilon_B = as \]

\[ a > 0 \]
Conclusion

Biological passive hygroscopic actuators

Continuous Systems with Abaqus®

(a) Mirror plane
(b) Rotation axis
(c) Symmetry restricts the space of possible movements

Point-Spring Systems with Rhinoceros®

Initial prestressed state

- Bending
- Twisting
- Helix

Final relaxed state

Compression
Tension
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