Materials strategies and systems for Soft Robotics

George Jeronimidis
University of Reading, UK
• Materials Systems in Biology – Bio-inspiration

• Soft Robotics

• Materials Strategies

• Conclusions
Virtually all material systems in biology are fibre-based.

- Cellulose: (Elastic modulus 150 GPa)
- Collagen: (Elastic modulus 1-10 GPa)
- Chitin: (Elastic modulus 120 GPa)

“Softness” in biological structures is a key factor in interacting with “noisy” environments and in responding to external and internal forces.
In some fibrous systems the modulus can be tailored using stiff ceramic materials: graded stiffness (tendon-bone attachment).

Fibres are not very good in compression: tensile pre-stressing via pressure or muscle actions (turgid plant cells) or “locking” via cross-linking (lignified plant cells).
Collagen and elastin fibres in blood vessels
Tendon Hierarchy

Evidence:

- x-ray
- EM
- x-ray
- EM
- x-ray
- EM SEM
- EM SEM OM
- SEM OM

TROPO-COLLAGEN

3.5 nm staining sites

FASCICLE

64 nm periodicity

fibroblasts

waveform
or crimp structure

fascicular membrane

reticular membrane

Size scale:

1.5 nm
3.5 nm

10–20 nm
50–500 nm
50–300 μ
100–500 μ
Octopus arms - Hydrostats
Gecko’s setae for adhesion
Same mechanism in insects and tree frogs (wet environment)
Hierarchies of compliant elements inspired by gecko setae
“Soft” systems in plants using high modulus cellulose fibres

Opening and closing of stomata on leaves to control gas exchanges in plant leaves

Leaf folding in Mimosa pudica (3 seconds)

Venus fly-trap (Dionaea muscipula) 10 ms to trap the insect

Leaf deployment controlled by turgor pressure and growth
Every cell is essentially a micro-hydraulic actuator

**EXPANSION - CONTRACTION - ELONGATION**

The pressure $P_T$ which can be generated can be as high as 20 bar (10 times the pressure in a car tyre) !!!!!
Modulation of fibre orientation

Trunk reorientation from tension wood in hardwoods

Reaction wood is used by trees to modulate shape of trunk and branches (gravitropism / phototropism– reorientation of axes)
Statololiths are a specialized sensory system in living cells involved in gravity perception by plants and most invertebrates.
Massive bending bimorph actuator

Coutand et al., 2004; B. Clair (2001)
Range of “soft” biological animal systems and typical fibrous architectures
Cross-helical arrangement of collagen fibres in tunicates (squids, etc.)

Internal liquid pressure generated by muscle action

Similar fibre arrangements are found in many animals with hydrostatic skeletons
Deformability is achieved not by having intrinsically soft materials but by exploiting fibre architectures in 1D, 2D, 3D

Orientation
Hierarchies
Water
Interactions: fibre-fibre, fibre-matrix, fibre-fluids

ALMOST INFINITE “DESIGN SPACE”
DIFFERENTIATION AT THE "MATERIAL" LEVEL
(Anisotropy, Heterogeneity, Hierarchies)

FUNCTIONAL INTEGRATION AT THE STRUCTURE OR COMPONENT LEVEL
Soft Robotics:

Deformable, compliant, low stiffness, ....

System level
Component level
Material level

Soft by nature or Soft by design
FIBRE SYSTEMS:

- metallic (including SMA)
- glass (including optical fibres)
- piezoceramic
- carbon (conductive)
- polymeric
- CNTs

Textile technologies are particularly suited to manipulate fibres, create shapes, integrate functions
Textile Technologies

Weaving
Knitting
Braiding
Fibre angle variation in braided tubular structures
KNITTED FABRICS FOR EFFICIENT, RELIABLE JOINTS
Nano-extrusion of 3D structures using gel-type carriers (nozzle) immersed in coagulation medium (drop) on glass substrate

Fibre systems are being incorporated in the process
Pressure-Strain (Deformation) vs Fibre Angle

Low compliance system

Figure 1a. Composite laminate structure under in-plane biaxial loading
Figure 1b. Deformation of cylindrical tube under pressure

Figure 2. Axial and hoop strains in balanced braided or filament-wound cylinder under internal pressure
High compliance system

“FESTO” – Pneumatic Muscle
Swelling of gel and encapsulation in fibre structure leads to contraction of structure and force generation
Computer simulations (Finite Elements) of shape changes in biomimetic structures inspired from turgid plant cells, based on active polymer gels integrated with braided fibre structures.
Changes in elastic properties with fibre angle (anisotropy)
Challenges

• Non-linear response (materials, geometry)

• Modelling aspects

• Self-repair

• Fatigue performance

• Fabrication limits / new fabrication routes (3D printing)
Conclusions

• Fibres can provide a very extended design space (shape, geometry, deformability)

• Potential for highly integrated systems (load bearing, actuators, sensors,...)

• Jointless structures (smooth load transfer)

• Available fabrication technologies, scalable
“The real voyage of discovery consists not in seeking new landscapes but in having new eyes”

Marcel Proust