Biomimetic Spatial and Temporal (4D) Design and Fabrication

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Abstract: We imagine the built environment of the future as a 'bio-hybrid machine for living in' that will sense and react to activities within the space in order to provide experiences and services that will elevate quality of life while coexisting seamlessly with humans and the natural environment. The study of Hierarchical design in biological materials has the potential to alter the way designers/ engineers/ craftsmen of the future engage with materials in order to realise such visions. Current techniques for making/ experimenting/ developing ideas are limited. Innovations in digital manufacturing technologies such as jacquard weaving and 3D printing promise the realisation of beneficial architectures from micro to macro scale previously impossible to achieve using conventional methodologies. This poster presents a novel landscape of opportunities for the exploration and exploitation of biological mechanisms into human centred manufactured systems.

1. BioExplore

BioExplore is one of the themes running in P^{3}i[i] Studio/Labs that is part of Northumbria University, Faculty of Art, Design and Social Sciences. BioExplore is dedicated to the technology transfer of useful ideas from biology into the man-made world to inform the design of autonomous multifunctional products and systems that will support and enhance the lives of future individuals. We imagine a shift from the current passive man-made environment to one that is multisensory, intelligent, responsive and anticipatory, where advanced skins and surfaces fuse human and built environment into a synthetic, 'post-biological eco-system'. As engineers, scientists, designers we can begin to unpick the how, what, and why necessary to make the transition from passive to active environments thanks to recent (last 20 years) advances in material science, chemistry and manufacturing technologies.

The study of structural hierarchy in biological materials can alter the role of material selection in the design or engineering process. Nature shows us that you can achieve advanced, complex behaviours combining simple materials in clever structural composites. The driver behind this is survival; organisms in nature rarely exist in environments with surplus resources, therefore those that fail to optimise the use of raw materials simply do not survive. Although in time, we will probably run out of the resources we currently rely on to fabricate the 'stuff' around us, we have the luxury of inhabiting a surplus world with the ability to seek out and develop alternative ways of making things. There is much we can learn as designers from Nature's 'lean' operation.

'SYSTEM FORMS MATERIAL' Versus 'MATERIAL FORMS SYSTEM'

We rely on the properties of materials to deliver a system, so we currently operate in a space where the needs of the *system* inform the selection of *material*. We rely on the material to deliver properties such as strength, toughness etc. When we need a structure to demonstrate a specific property and we do not have a material that delivers the performance, we synthesize one that does. As a result there are over 300 man-made polymers used commercially.

In Nature protein and polysaccharide are the two main polymers that form the basis of all biological materials and structures(Vincent 2012). Variations in the assembly of these materials deliver the vast range of properties demonstrated in biological materials. Insect cuticle, for instance, is made from protein yet can be stiff or flexible, opaque or translucent, depending on the way the raw materials are put together (Vincent and Wegst 2004). In Nature, *material* forms the *system*.

If we look at the generic hierarchy of a single organism, there are nine levels of organised structural elements: atom, molecule, macromolecule, sub-cellular organelles, cells, tissues, organ, organ system and organism. The organisation of raw materials within and across each level is what enables the rich diversity in properties demonstrated by biological structures(Tirrell, Fournier et al. 1994). We tend to use less complex non-hierarchical design processes, generally because it is more cost effective to invest in material than skilled labour/ craftsmanship necessary to achieve more complex structures.

In this hierarchical classification, the Eiffel tower is a third order design while metal frameworks forming the skeleton of conventional skyscraper buildings are classified as first order structures. The structure of the Eiffel tower is an iron lattice work made from relatively short bars of metal bolted into a shape (1st order), these configurations are assembled into greater structures (2nd order) these in turn are joined to compose the tower (3rd order). The metal framework of conventional buildings is composed of long lengths of structural steel that are bolted together (usually at right angles) to form a 1st order structure.

Iron is a relatively weak material especially when compared to the qualities of structural steel used in construction today. Many believed, at the time of its erection, that the Eifel tower would collapse because the quality of the material used to make it was not strong enough to support the weight of the structure. In fact Lakes (1993) estimated that the relative density ρ/ρ_0 (density ρ as mass per unit volume of structure divided by density ρ_0 of material of which it is made) of the Eifel tower is $1.2X10^{-3}$ times that of iron, while the metal skeleton of a skyscraper has relative density $5.7x\ 10^{-3}$ of structural steel (Lakes 1993).

Designing with hierarchy can deliver strong structures from weak materials by managing strength and stiffness of composite systems. Lakes also studied the effects of Hierarchical design on viscoelastic properties of composite systems and structures with negative Poisson ratios. If this approach can deliver material systems with counterintuitive properties and metamaterials, can it aid us in the transition from static design to spatial and temporal engineering?

2. Biomimetic Realisation

Biomimetics has found long reaching applications from bytes and molecules to cities, both the digital and virtual worlds have adopted principles and applied them to their own methodologies and technologies. However, conventional making processes do not generally lend themselves to mimicking complex architectures. Layered manufacturing methodology is a very effective way of exploring layered mechanisms to produce artificial muscles and smart soft composite prototypes cheaply and efficiently(Weiss, Merz et al. 1997; Ahn, Lee et al. 2012) but are limited to linear structures.

Jeronimides et al (1980) discovered that the mechanism behind the stiffness and ductile behaviour of wood is due to the microfibril orientation of cellulose molecules in the S2 layer of the wood cell wall. The team were able to upscale the nano mechanism into a micro-macro scale design however, in order to build the prototype, which relied on accurate controlling the orientation of the fibres within a matrix, the team had to design and build a custom machine(Jeronimidis 1980).

Milwich et al (2006) combined ideas stemming from microfibril orientation in wood fibres with the design of the stem of the giant reed to create a hybrid model realised using advanced braid protrusion machinery at the Institute of Textile Technology and Process Engineering (ITV) Germany. The outcome called ‘Technical plant stem’ is a commercially scalable textile composite that combines high strength and impact resistance with minimal use of material for applications in the building sector (Milwich, Speck et al. 2006). The use of specialised textile machinery enables complex geometries to be realised, tested and commercialised.

In recent unpublished work, we have begun to explore spatial and temporal design in woven structures using simple materials and traditional weave methodologies. By studying the shrinking effects of wool in hot water combined with effects of weave and yarn structure we engineered a 2D layered textile that when cut off the loom resembled a 2D flat, rectangular piece of cloth, yet when exposed to hot water, the material was transformed into a fully fashioned vest with design details without the need for further processing i.e. cutting and sewing. This simple project we call “Loom to Hanger” demonstrates that a shift in thinking about materials can deliver structures that move from 2D design to 4D spatial and temporal engineering.

Recent advances in 3D printing technology in terms or resolution (micron versus previous millimetre scale) and range of useable materials have created a new platform for the exploration and experimentation of biologically inspired stimuli responsive 4D systems. This state of the art equipment is currently used in the biomedical sector for the creation of tissue scaffolds, which draw on the fine resolution capacity and the ability to print using high spec biomaterials (Cohen, Malone et al. 2006; Moroni, de Wijn et al. 2006).

We have identified the design principles behind hygroscopic seed dispersal mechanisms primarily in dehiscent legume pods as an ideal paradigm for technology transfer. Study of the hierarchical system reveals that the seedpod valves are simple bi-layers systems composed primarily of cellulose. Depending on the degree of difference in orientation of the cellulose microfibrils between these layers, the pods either twist or bend in dry conditions but always revert to their original shape when exposed to moisture. We are exploring this mechanism for the design of 4D composite systems using the orientation capabilities of advanced 3D Fibre deposition and digital weaving technologies. The outcomes will be documented and characterised (where appropriate) using optical microscopy, AFM, SEM, moisture sorption analysis, wettability and motion capture. We wish to present an overview of this work in progress.

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[i] P^3i stands for Printable, Paintable, Programmable ‘intelligent’ systems