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Mutate: The Evolution of a Responsive Knit Design System

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Abstract: This smart textile design research is located at the intersection of biomimicry and responsive material systems. Using the inherent properties of natural fibres and knit structure, the aim is to develop responsive knitted fabrics, which question the conventional material systems necessary for smart textile design.

The work is informed by biological models derived from biomimetic research. Underpinning design research is a functional analysis of the responsive capacities of plants. This research is manifested through a framework derived from specific biomimetic models; the pine cone hygromorph, and the hierarchical nature of plant materials. This framework is mapped against the fundamental components of a knitted fabric to establish a hierarchical model of knitting. Using this model a collection of knitted prototypes, constructed exclusively from natural fibres have been developed. These fabrics transform from 2D to 3D in response to changing moisture levels.

Whilst potential applications span the textiles sector, the impact of this research is more profound. This work represents a shift in thinking about responsive textiles. Rather than applying complex synthetics or e-textiles, my practice re-examines natural fibres and textile processes. Through the systematic application of a hierarchical model derived from biomimicry, a zero energy, 100% natural, responsive material system has been established.

Keywords: Knitting; Biomimicry; Responsive material systems; Smart textiles.

1: Context

The way we think about materials is changing. Digital sensing technologies and new manufacturing methods have allowed designers to develop whole new classes of responsive, shape changing, smart materials. Textiles, with their inherent flexibility provide an excellent substrate to materialise shape change. Using shape memory polymer, alloy and electro-active polymers, designers have developed a new class of transformable textiles for fashion and interiors applications. There are two conventional methods to incorporate responsive functionality into textiles; either using the textile as a substrate for the application of smart of conductive materials, or by introducing conductive yarns or smart materials into the textile during knitting or weaving.

Biomimicry provides a completely different framework for the exploration of responsive textiles. Biomimicry is a research method that focuses on the functional analysis of natural forms, processes, and systems, in order to develop sustainable design solutions (Benyus, 1997). The responsive capacity of nature is fundamental to all biology. Plants respond to a variety of stimuli, including light, gravity and touch. Whilst these responsive systems are active, controlled by the plant hormone auxin, there is another class of movements which can be described as passive (Scott, P, 2008). Here, the sense and response system is a result of the structuring of the material itself.

Knitted fabrics are inherently flexible and extensible, however they can also be described as anisotropic, or unbalanced, a property materialised in knit in the way a fabric curls. Yarns can be designed to share this characteristic, by varying the direction and amount of twist inserted during the spinning process. In combination with the natural moisture absorbing properties of protein and cellulosic fibres, I have established a responsive material system for knit design.

This paper examines the evolution of this system, and explains how biomimicry has informed all stages of the design process. The research is materialised through Mutate; a collection of responsive knitted fabrics, composed exclusively from natural materials that transform from 2D to 3D as moisture levels fluctuate.

The importance of this work goes beyond the design of individual shape changing fabrics, focusing rather on how my experimentation has led to the design of a methodology which integrates fibre, yarn, fabric and form into a responsive material system. The implications of my research are, firstly, as a model for the application of biomimicry as a design methodology, secondly, as a new system for the design of programmable materials, and finally as a novel system to construct shape changing textiles.

Figure 1. Fabric Testing, (Scott, 2014)

The outcomes comprise experimental prototypes Coil, Shear, Meander, Shift; a shape changing garment, and Skew; an interior panel. The diversity in exhibited pieces represents the scope of the material system. Fabrics are knitted on Shima Seiki Mach2S 12gg power machine, programmed using the APEX3 system. Fabrics are composed of wool, linen and silk. Film is an important documentation method in my work. Whilst it is possible to demonstrate the actuation process, all exhibited work will be supported by film documentation.

2: Process: A Biomimetic Methodology

To understand the design method it is critical to explore the concept of hierarchy, and how it translates from botanical source material, to knitted fabric design.

In order to achieve responsive behaviours in knitted fabrics, I examined the functional role of each parameter - fibre, yarn, fabric, and form. To formalise my thinking, the hierarchical structure of plant materials was deconstructed and mapped against the knit parameters (fig 5). This model provides a method to map the requirements for a responsive design system, against components of knit fabric. The outcome is a means to design knit fabrics with inherent programmability.

Plant materials are naturally hierarchical; each level is responsible for controlling and adapting certain functionalities (Gibson, 2012). The plant material hierarchies outlined in fig 5, identify the functional role at each level, and provide a visualisation of the impact of a hierarchical system. The overall plant morphology is determined through a combination of the other hierarchies working within the system. Each level is extremely important. For example, the structural role played by cell walls is modified by the orientation and length of its microfibrils. These vary as the cell walls develop (Gibson, 2012). The orientation and length of the microfibrils provide the mechanical properties to support individual cells themselves, but equally, as a cell wall, they provide the underlying framework for the whole plant (Burgert, 2013).

Any knitted fabric can be analysed in a similar way; at least 3 hierarchies are present in all knit fabrics; fibre, yarn and fabric (Eadie & Ghosh 2011). In addition to the three hierarchies identified by Eadie and Ghosh, I add a fourth; form. This hierarchy provides the means to establish the most complex geometries through increasing and decreasing the number of stitches knitting, and through partial knitting where stitches are held to generate 3D form.

The properties of a knitted fabric can be modified by changes at any level of the hierarchy (Scott, 2013). For example the extensibility of a knitted fabric could be changed by changing the fibre (wool is more extensible than linen), the yarn, (a low twist yarn is more extensible than a high twist yarn), or the fabric structure, (by incorporating tuck stitches a fabric can become more extensible across the width). These properties can change across all levels of the hierarchy, or at a single level. To design responsive, shape changing fabrics, sensing and actuation need to become inherent to the fabric. In my work the environmental stimuli which triggers the 2D to 3D shape change is moisture (Scott, 2013).

The moisture absorbing properties of natural fibres are well known; it is this property that allows clothing to absorb moisture from the skin, and it is fundamental to traditional laundering processes. (Morton & Hearle,1986). However the challenge for this design research is to engineer a physical change in the fabric as a response to natural fibres absorbing moisture.

To examine this principle I identified a specific biomimetic model where changes in humidity cause a physical change in shape. This is observed in pine cones, where the individual scales open and close as moisture levels fluctuate. In terms of a biomimetic model the critical aspect of the pine cone model is the orientation of the fibres within the individual scales, and how they react to changing humidity. There are two different orientations; on the upper part of the scale fibres are orientated along the cell axis, and as they dry out shrinkage occurs perpendicular to the cell axis (Vincent, Dawson & Rocca, 1997). On the bottom of the scale, fibres are orientated perpendicular to the scale and these fibres shrink in the axial direction.

Hierarchical Structure of Plant materials		
	Hierarchy	Description of Adaptive Growth
1	Cellulose microfibrils	Length and orientation of microfibrils determines anisotropy of cell wall. This influences cell shape, geometry, and mechanical properties.
2	Cell wall	Primary and 3 secondary walls (S1,S2,S3). Different orientation of cellulose fibres in each layer. Fibre orientation in S2 layer, cell size, wall thickness, and chemical composition, adjusted for required performance.
3	Cells	Optimised lightweight structures due to cell wall organisation, eg: honeycomb, foam-like polyhedra.
4	Morphology	External structure: shapes of leaves, stems, growing habits.

Hierarchy in Responsive Knit System			
	Hierarchy	Variables Explored Within Research	Function in Responsive Knit System
1	Fibre	Cellulosic (linen) Protein (wool, silk)	Sensing and actuation.
2	Yarn	Twist factors; degree and direction.	Actuation and form generation.
3	Fabric	Single and double bed fabric.	Form generation: final geometries.
4	Form	Shaping, partial knitting.	Form generation: final geometries.

Figure 2. Hierarchical System: Comparison of Hierarchies in Plants, and Knitted Fabrics. (Scott, 2013, adapted from Gibson 2012, and Burgert, 2013)

The combined action of the tissue layers leads to a bending of the scale, opening the cone (Fratzl, Elbaum & Burgert, 2008). In addition to this, the geometry of the individual scale allows the swelling and shrinking effect within the central area of the scale to act over the whole scale, amplifying the movement (Vincent, Dawson & Rocca, 1997).

3: Outcomes: Mutate, Environmentally Responsive Knitted Textiles

To test the biomimetic method I have developed a series of knitted prototypes. Composed of linen, silk and wool, the fabrics transform from 2D to 3D when there is a change in moisture levels in the environment. The responsive behaviours are demonstrated in the following knitted fabrics:

1. Coil
2. Meander
3. Shear

In each fabric, different elements of the hierarchical system, outlined in fig 5, are explored. Each prototype incorporates high twist yarns composed of different natural fibres, mapping against levels 1 and 2 of the hierarchy (H1 & H2). Coil illustrates how the relationship between face and reverse stitches produces an actuated geometry (H3); Shear presents a more complicated arrangement of stitch transfer (H3), and the complete system is integrated in Meander (H3 & H4). Each design is recorded graphically using notation based on the Shima Seiki programming language. The work has been filmed, and access to video documentation is available at: http://vimeo.com/109918994.

3.1: Coil

Coil is a composed of 100% merino, and knitted on a 10gg double bed machine. The fabric is constructed using front bed (FB) and back bed (BB) stitches arranged 60 FB, 60 BB. After knitting 60 courses all stitches are transferred to the opposing needle bed and then another 60 courses are knitted. This sequence is repeated 4 times. (figs 12 & 13). The yarn used is 2/30's nm merino with Z twist inserted at 1000 turns per metre. The yarn information is of particular importance for two reasons. Firstly, the fibre composition; merino wool is characterised by long, fine, hydrophilic fibres (Morton & Hearle, 1986). Secondly, the twist inserted into the yarn during the spinning process is classed as high twist, producing a particularly lively handle. On actuation the fabric coils around the central point of interaction between front and back bed stitches, exploiting the opposing directionality of the face and reverse stitches (fig 12).

Figure 3. Shear, machine state (Scott, 2014)

Figure 4. Shear, actuated centre (Scott, 2014)

Figure 5. Shear, actuated, left side

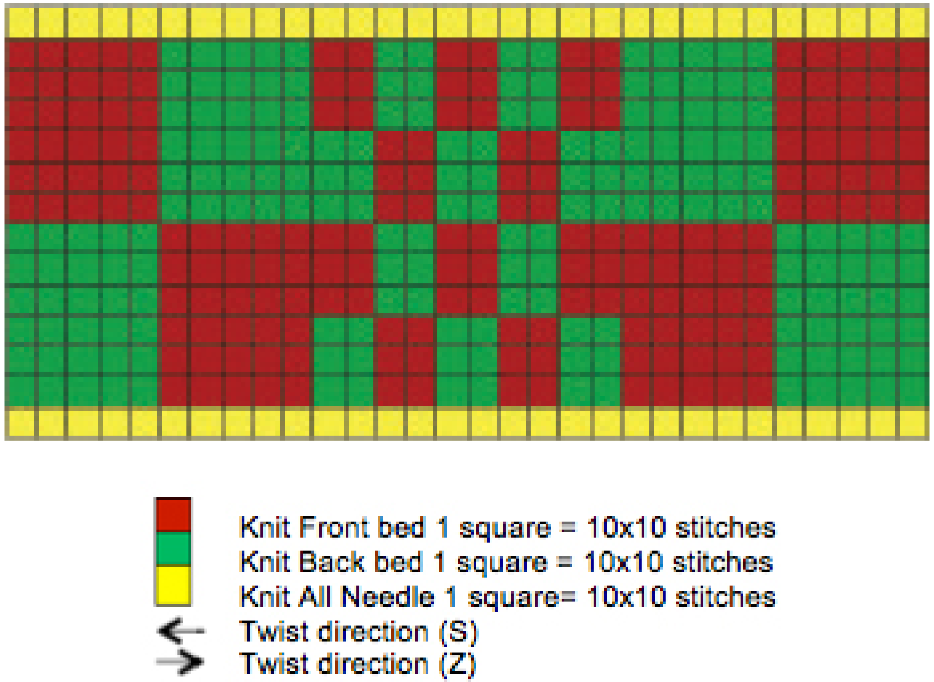

Figure 6. Shear: Technical Notation

3.2:Shear

Shear is composed of 100% linen. The yarn is 1/24nm high twist with 880 turns per metre in the S direction. It demonstrates how the responsive knit technique described above can incorporate more complex configurations of stitches enhancing the 3D profile (figs 3, 4 & 5). The fabric contains different scales of repeating units. Analysis of the outcome indicates that changes of scale impact not only the individual units, but also lead to alternative geometries at the intersections of different areas, due to the continuous nature of the surface. Shear also contains an all needle edging which is a balanced structure. This part of the fabric also transforms from flat to an undulating form, because of its connection to the responsive material.

3.3:Meander

Meander demonstrates a complex iteration of the responsive knitted system (figs 9, 10 & 11). In this prototype the properties of two materials are explored; linen and silk. To add complexity the two yarns have different directional properties. The linen is 1/30nm Z twist 880 turns per metre, and the silk is S twist, 1100 turns per metre.

Another knit specific geometry is explored, the potential to shape the material as it is constructed (H4). Here the notation assumes the following: rate of transfer 1 needle per two courses in the direction

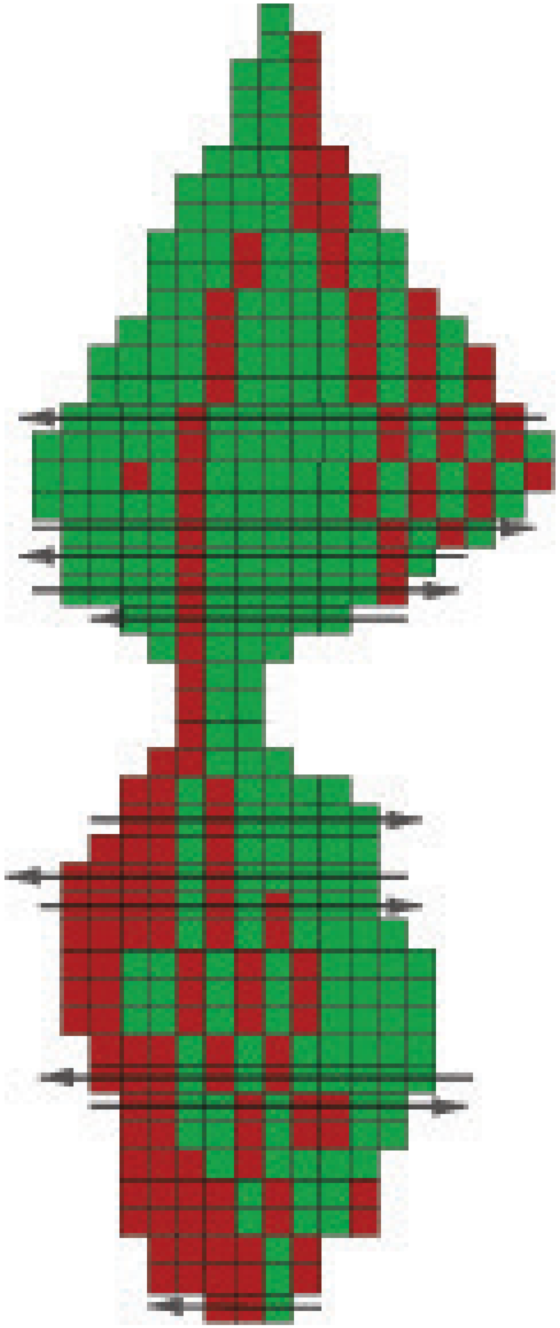

Figure 7. Meander; technical notation. (Scott 2014)

Figure 8. Meander, Machine state. (Scott, 2014)

indicated. The simplification of the notation system (compared to the traditional 1:1 programming) prioritises the relationship between directionality of stitch, (critical to the shape changing properties), over the construction notes (required for manufacture.) As I have both designed and knitted the prototypes this shorthand has become a way to simplify the documentation.

Scale interacts in this fabric scale both the level of the individual stitch and the knitted form. The twist and curl exploited in the initial fabrics; coil and

Figure 9. Meander; detail showing where interaction of different materials enhances (a),and prevents actuation (b). (Scott, 2014)

Figure 10. Meander: This fabric combines silk and linen with opposing orientation (twist direction) in combination with irregular patterns of stitch transfer to produce organic curls and folds when actuated.

shear, are both enhanced in areas of repetition (a), and diminished in areas where opposing directionality in both structure and material intersect (b) (fig 9).

4: Analysis and Implementation: Designing the System

Whilst the design of individual fabrics demonstrates the potential of this new class of responsive, knitted textiles, in order to implement a change in the way we think about smart textiles, the design system needs to be clearly articulated. Architect Skylar Tibbits has developed 4D printing, a method to design programmable materials using 3D printing techniques (Tibbits 2012). His methodology references self assembly, producing objects that change from one programmed form to another actuated by different stimuli. Tibbits identifies four key components to make the process work:

- simple assembly sequences
- programmable parts
- force of energy or actuation
- error correction and redundancy" (Tibbits 2012, 69)

In conventional notation systems a particular configuration of materials and structures is presented to document a specific outcome; Tibbits' system focuses instead on the underlying components required to make

Knit Hierarchy	Function in responsive knit system	Variables explored	Programmable variables
Fibre *force of energy or actuation*	Sensing and actuation	Cellulosic protein	1: Expansion 2: Contraction 3: No change
Yarn *programmable parts*	Actuation and form generation	Twist: degree/ direction	1: Skew Left 2: Skew right 3: No change
Fabric *simple assembly sequence*	Form generation and final geometries	Single/double bed fabric	1: Curl towards FB 2: Curl towards BB 3: Stable

Figure 11. Components of The Responsive Knit System (RKS) (Scott, 2014) Incorporating rules of 4D Printing (Tibbits, 2012)

the system operate. These components can operate in a multitude of different configurations. This is a useful method to apply to my research, in order to identify the relationship between each component in the knit hierarchy. The potential of applying this kind of system, is that alternative materials or stimuli could be switched into the system in order to change the application. For example, whilst current iterations are moisture responsive, an alternative stimuli could be introduced as long as the other variables correspond to the change.

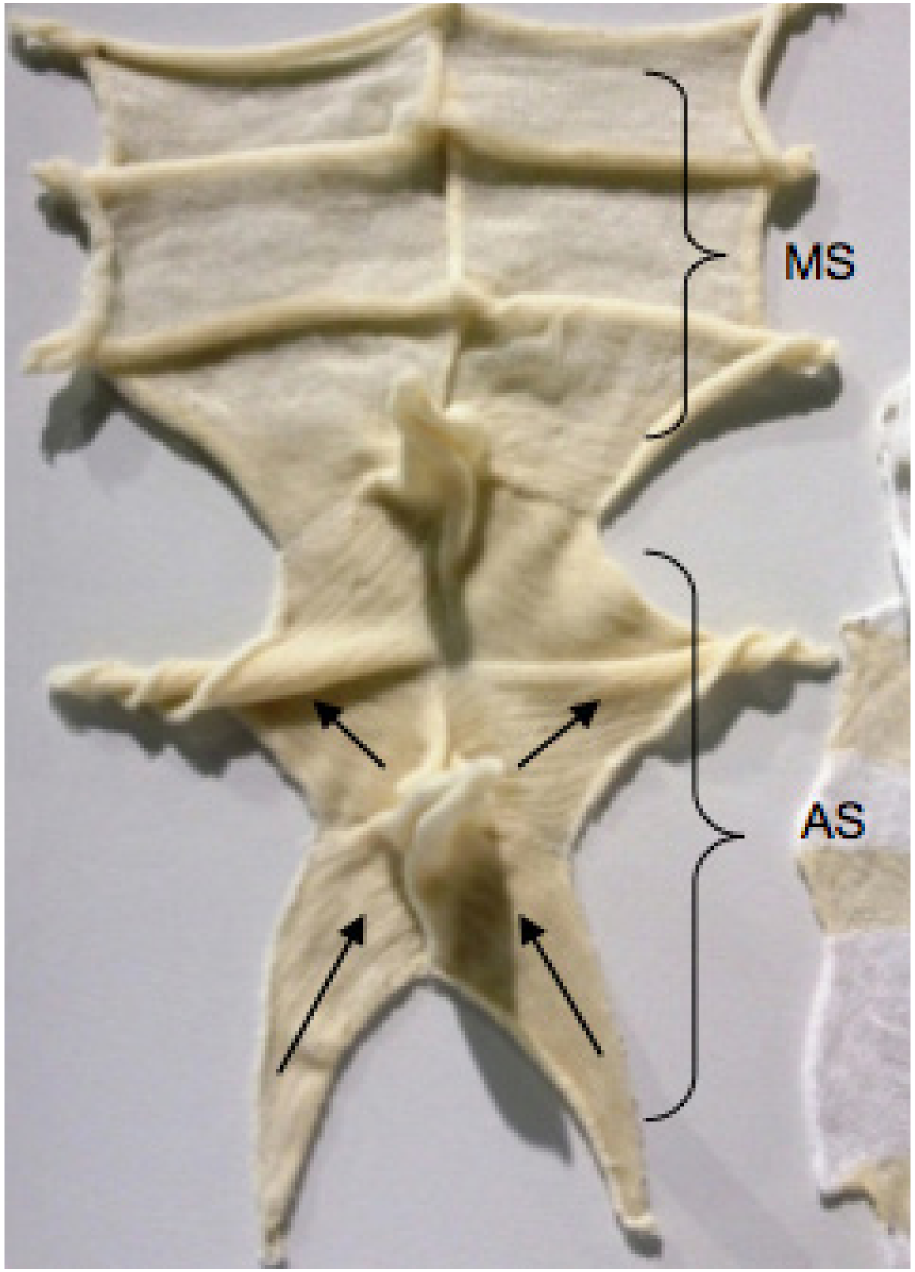

Figure 12. Coil; illustrating both machine state (MS)(top) and actuated state (AS) (bottom). The arrows indicate the movement of stitches, for this particular configuration of FB and BB stitches.

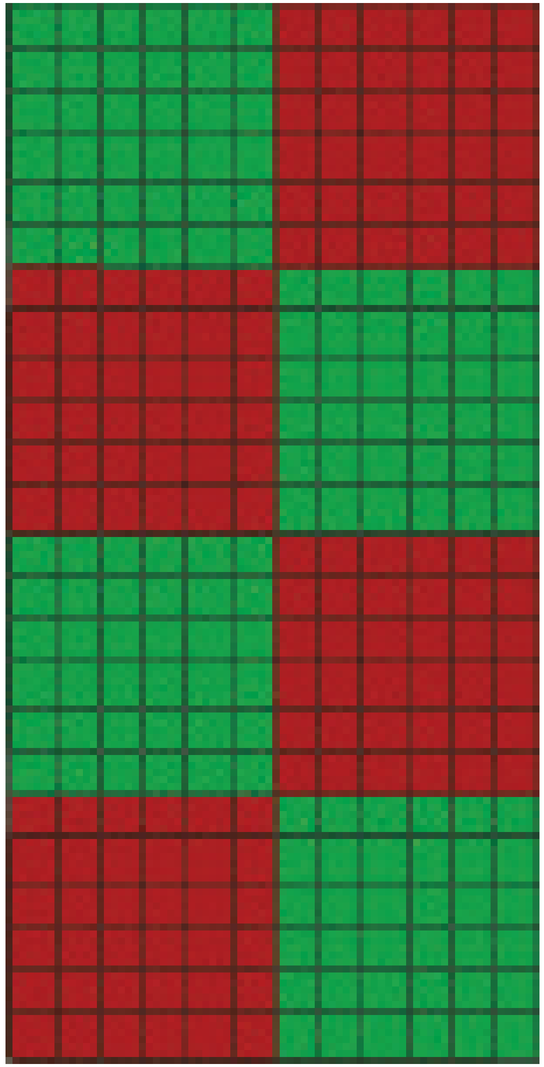

Figure 13. Coil: technical notation. (Scott, 2014)

Figure 14. Skew generated using directional twist on plain knit fabric. (Scott, 2014)

Figure 15. Links/links fabric (Scott, 2012)

Figure 16. Pleated fabric (Scott, 2012)

4.1: Fibres/Actuation mechanism

Both cellulose and protein fibres have dynamic moisture absorption properties; fibres swell and increase in volume in the presence of moisture. Fibres swell almost entirely in the radial direction, and there is little observed change in the overall length of the fibre (Stamboulis, Baillie & Peijs, 2000).

The dimensional change at a local scale within individual fibres is amplified throughout a knitted structure because fibres are not used individually, instead they are spun into yarns in a systematic way. This creates a pronounced and predictable dimensional change on a global scale, providing the underlying actuation mechanism to the system. The three variables are as follows:

1. Expansion
2. Contraction
3. No change

4.2: Yarns/Programmable directionality

As previously discussed the orientation of microfibrils in the secondary cell wall of plant materials imparts many of the plants mechanical properties. The orientation of fibres in knitted textiles is controlled by the yarn and the fabric structure. Yarns are composed of a multitude of individual fibres which are aligned and twisted together during the spinning process. Twist is inserted in a yarn in either a clockwise (Z), or anticlockwise (S) direction, producing yarns with directional properties. Conventional yarns are engineered to have balanced properties, by folding or plying ends together. However it is possible to exaggerate their unbalanced nature through increasing the amount of twist. High twist yarns have between 800-1000 turns per metre (Taylor, 1999).

Knitting with high twist yarns changes the resultant geometry. The conventional loop shape becomes skewed. Whilst the dimensional change of an individual loop is minimal, once this is amplified across a series of courses and wales, the change in geometry becomes more significant (Spencer, 2001).

For a single bed fabric knitted on the front bed the following variables are possible:

1. Skew Left (S twist)
2. Skew Right (Z twist)
3. Stable (balanced twist)

4.3: Fabric/Assembly sequence

Single bed fabrics are composed of loops of yarn constructed in the same direction; either on the front or back bed of the knitting machine. These fabrics are unbalanced because the yarn is always drawn through the old loop in the same direction. The result of this is that that fabrics curl (Spencer 2001). They always curl in the same way towards the technical front at the top and bottom, and towards the technical back at the sides. It is possible to combine face and reverse stitches in the same horizontal course (row), and to transfer between these states on subsequent courses. This allows the directionality of the fabric to be programmed as it is constructed. It is this characteristic that produces pleated fabrics and 3D effects using links/links technique. Knitting on both needle beds creates a balanced fabric which does not curl, characteristic of ribs on the cuffs of garments. The assembly sequence required for shape changing knit fabrics is based on only three options:

1. Curl towards front bed (knit back bed)
2. Curl towards back bed (knit front bed)
3. Stable (knit both beds).

My research demonstrates that knitted textiles have a unique capacity to modify their shape and form due to the relationship between their interlooping construction and their material composition.

5: Reflections

Smart Textiles and the Responsive Knit System

One aim of my design research is to critically address the conventional understanding of material systems for the development of responsive textiles. Within a traditional model the textile can either provide a substrate for the application of smart or conductive materials, or the conductive yarns and smart synthetics can be woven or knitted in to the textile during manufacture. The problem with this methodology is that it is hard to achieve a synergy between the textile and the material components. If textiles are used simply as a flexible substrate, or method to conceal conductive materials, the unique properties of the textile itself become secondary to the technology.

Through a re-examination of the properties of conventional knitted fabrics using biomimicry, a hierarchical model has been developed that exploits the natural responsiveness of textile materials and processes. In this design system natural fibres act as sensors and actuators to a system which senses changing moisture levels in the environment. Shape change is controlled by yarns and knit structure, and the fabric itself determines the final geometries as it transforms from 2D to 3D. The careful application of all aspects of the textile: fibres, yarns, fabric, and form, means that rather than applying additional technology to a knitted substrate, my work embodies the nature of knit itself as a responsive form.

There are several wider implications of my research. Firstly, all stages of the design process are informed by biomimicry, and, in doing this, my research systematically applies a specific biomimetic model. The outcomes demonstrate the potential for biomimicry to fundamentally re-imagine design problems from a functional perspective, leading to novel innovations.

The second, more fundamental implication of my research is that whilst technology drives much innovation in design, my practice demonstrates that it is possible to achieve smart functionality by re-evaluating conventional materials and processes. Although my research focuses on knitted fabric design, the ability to integrate structure and function through programming material systems (like the responsive knit system), opens up the potential for wider investigation using alternative components.

Finally, from a textile design perspective, my design practice demonstrates the potential to integrate responsive behaviour into knitted fabric. As such, a zero energy and 100% natural, responsive material system has been established.

References

Benyus, J. (1997). *Biomimicry: Innovation Inspired By Nature*. New York: Perennial.

Burgert, I. (2013) Materials Design Inspired by Tree and Wood Archtiecture. *RSC Smart Materials*, No.4 128-139.

Eadie, L and Ghosh, T. (2011). Biomimicry in Textiles, Past, Present and Potential, an Overview. *J.R. Soc Interface* 2011 # 59 (8): 761-775.

Fratzl, P. Elbaum, R. & Burgert, I. (2008) Cellulose Fibrils Direct Plant Organ Movements. *Faraday Discuss*: 139, 275-282.

Gibson, L. (2012) The Hierarchical Structure and Mechanics of Plant Materials, *J.R.Soc. Interface* 9 2749-2766 (doi.10.1098/rsif.2012.0341).

Morton, W.E. Hearle, J.W.S. (1986) *Physical Properties of Textile Fibres*. Manchester, Textile Institute.

Ritter, A. (2007) *Smart materials in architecture, interior architecture and design Basel*. Boston-Berlin, Birkhauser.

Scott, J. (2013) Hierarchy in Knitted Forms, Responsive Textiles for Architecture, in *proceedings of ACADIA2013*, Adaptive Architecture, Waterloo, Canada, 361-367.

Scott, P. (2008) *Physiology and Behaviour of Plants*. Wiley, UK.

Stamboulis, A. Baillie, C.A. Peijs, T. (2001) Effects of environmental conditions on mechanical and physical properties of flax fibers. *Composites Part A*, Vol32, Issue 8, 1105-1115.

Spencer, D.J. (2001) *Knitting Technology*. Woodhead, Cambridge.

Taylor, M.A. (1999) *Technology of Textile Properties*. London, Forbes.

Tibbits, S (2012) Design to Self Assembly, *AD* Vol82, Issue 2 68-72.

Vincent, J. Dawson, C. & Rocca, A.M. (1997) How Pine Cones Open Up. *Nature*, 390:18/25, 6661, 668.