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The Power of ‘Soft’

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ABSTRACT

Over the last decade, the explosion in research and Development associated with nanoscalar materials has continued apace. In parallel with this has been the rapid rise of both sustainable materials and, as a consequence, Natural, Cellular and Responsive material systems. Many of these originate from inorganic, inorganic-organic hybrid composites and polymeric and bio-nano polymeric systems which exhibit intrinsic physico-chemical properties that can be classed as ‘soft’. That is flexible, malleable, lightweight, transparent or semi-transparent and stretchable in character and which can also offer both biocompatible and bioresorbable characteristics essential to useable and sustainable material systems.

This paper describes some of the ways in which we are beginning to understand, explain and exploit ‘soft’ technology. In particular the interactive role of creative design and innovative material science linked through new fabrication methodologies that have, as their common purpose, a focus on compelling Human centred needs. Examples are health, wellness, ambient assistance and urgent improvements in cleanliness, hygiene and nutrition.

INTRODUCTION

Considering a Design:STEM Integration based approach to human centric applications, we are living in the age of electronics, bioscience and the promise of nanotechnology. Together they constitute early 21st century materials convergence and, when coupled to Design fundamentals, provide a compelling platform to deliver applications in human centric needs, wishes and behaviours. These manifest themselves through improvements in the way we investigate age related illness, mental wellness, medicine, personalised health monitoring, more sustainable transportation, beneficial consumer products and innovations in personal communication [1,2,3].

There is now an opportunity to consolidate a Design : STEM Interaction programme of research that will enable an exploration of compelling artefact, product and service pathways through the integration of soft, responsive, stretchable, biocompatible material systems that can be readily coupled to new fabrication tools and methodologies to meet the vision of practical, ‘calm ambient and personally meaningful technology’ and the application of conformable polyvalent surfaces through the accelerated integration of miniaturisation and possibly printed organic electronics.

DESIGN: STEM INTEGRATION

The research programme of the P³i team (Printable, Paintable, Programmable materials that can generate the basis for intelligent systems) builds on more established methods of semi conductor fabrication, for example, lithography, stamping and patterning. In addition, the development of specific methodologies within Additive Manufacture such as direct write laser processing, 3D printing and innovation through printed electro/photo active materials. When coupled to the patterning, cutting and structuring skills employed in design, it is possible to generate new ways to create environmentally responsive surfaces and interfaces exploited through intrinsic properties of polymers, gels, elastomers and soft biomaterials. We term this convergence ‘soft’, programmable material systems and we have been examining how best to utilise foldable, responsive, stretchable, tissue-like material films and structures that can exhibit beneficial physical, sensory and digital effect signatures that have the potential to positively improve people’s lives through anticipatory healthcare, convenience, connectivity and improved interactions and innovative approaches to sustainable human centred products and services.

To illustrate our approach, an obvious starting point here was the search for responsive, stretchable materials and the tools to fabricate them. This is an essential exercise because all too often, new material technologies which we perceive to be different turn out not to be better than what is often already available. This is one of the reasons to be cautious concerning the evolution of nanoscience into implementable and scaleable nanotechnology, as is the case currently with ‘3D printing’ which, although a subset of additive manufacture, is currently limited to a relatively small number of polymeric materials with compatible thermo-physical properties and nearly always require additional post processing and finishing.

The outcome of our initial work therefore has focussed on the ‘rubber band’ in the form of conductive, capacitive functional acrylic and polyurethane elastomers. The initial activity has focussed on ‘on-body’ sensing but has developed rapidly into a more wide-ranging examination of stretchable or strainable devices building on the pioneering work by John Rogers’ group at the University of Illinois at Urbana [3, 4]. Printed and Stretchable electronics, when coupled to responsive materials such as environmentally triggered polymers and gels, have begun to point the way towards more digital-physical fusion or integration. Some of the materials, systems and effects are summarised below.

Table 1: ‘Soft’, responsive, functional material systems

Electro and photo active polymers and elastomers	EAPs
Environmentally responsive polymers and hydrogels	ERHs
Chromogenic materials	CGMs
Polymer opal composites	POCs
Shape memory polymers	SMPs
Stretchable and conductive polymers	SCPs
Ultra low density polymers	ULPs
Biomimetically structured materials	BSMs

Table 2: Environmentally triggered responsive materials

Environment	Response	Materials
pH change	Colour change	Halochromics, Hydrogels
Applied pressure	Colour change	Piezochromics
(Mechanical stress)	Capacitance change	Di electric elastomers, EAP's
Temp change	Volume (swelling or shrinkage)	Shape memory polymers
	Hydrophilic to hydrophobic switching	Thermochromics Hydrogels
Light		
Applied pressure (pneumatics)	Volume, Shape	Shape memory polymers Hydrogels
Applied stretch (mechanical strain)	Soft to stiff (reversible) & Texture	Elastomeric or polymeric composites
	Colour change	Polymer Opals
	Capacitance change	Piezopolymers

From the initial responsiveness and switching capabilities of these soft, functional material systems, we can now envisage their practical usefulness for example, as follows:

- a) Multiple HAPTIC concepts utilising shape change, surface roughness control, texture and volume change that can be used in human body rehabilitation. [1]
- b) Ambient (calm) sensing and responsiveness 'on-body' and 'around body' utilising temperature, stretch (strain), sweat/moisture content, pressure, pH balance and light for potentially non-invasive actuation and even anticipatory preventative personalised medical devices and hence effective healthcare out of hospital. [3]

EXPERIMENTATION: AN EXAMPLE OF 'SOFT' STRETCHABLE SENSING

Design-led, materials based approach to human centred applications using modified dielectric electroactive polymer sensors

This example describes an exploratory study carried out by our design-led interdisciplinary research group that explores future ways of living through materials and technology interrogation to determine and demonstrate innovative interventions that resonate with the way we experience our material world [14]. We recognise that the products of tomorrow have to 'do more with less' in order to attempt to meet the societal challenges of the 21st century. A significant domain for smarter products is within assistive healthcare [5, 6]. Products that incorporate sensors and sensing are increasing and have a pivotal role in assistive healthcare and personalized monitoring [7]. However, sensors, actuators and other electronic components are frequently made of rigid and stiff materials that limit their incorporation into products and the type of product that they can be used for. Much work has been done in the area of smart textiles, integrated sensors and wearable computing [8, 9].

In recent years however, two major developments are changing the form and function of sensors and their incorporation into wearable or on-body solutions. One is conductive polymers (high electron mobility) that can be solution processed and hence form the basis for printable sensor fabrication via ink jet and screen printing technology [10]. The other is stretchable electronics which are light, flexible and can withstand robust handling [11, 12]. Of particular interest is the class of stretchable electronics based on electro-active or electro-responsive polymers (EAP's).

Materials and methods

Of these, we have chosen to examine dielectric electro active polymers (DEAP) in some detail because they offer a large degree of freedom in terms of their strain behaviour under an applied electric field [6, 7, 8]. The DEAP basic structure is made up of a film of a dielectric elastomer material that is coated on both sides by another expandable film of a conducting electrode. When voltage is applied to the two electrodes a Maxwell pressure is created upon the dielectric layer. The elastic dielectric polymer acts as an incompressible fluid which means that the electrode pressure comes the dielectric film to become thinner in the 2 directions and expansive in the planar directions (x,y). When this occurs, the electric force field is converted to mechanical actuation and motion.[21]

We explored the DEAP sensors developed by the Danfoss company in Denmark which have the added benefit of specific electrode shape and topology which gives use to an accentuated movement in either the x or y direction with the other constrained to the mechanical structure of the assembly [7]. DEAP are intrinsically position or strain sensors. DEAP sensors have certain advantages even when an actuation function is not included. The large strain characteristics and environmental tolerance of DEAP materials allow for sensors that are simple and robust. In sensor mode, it is often not important to maximise energy density since relatively small amounts of energy are converted. Thus the selection of DEAP materials can be based on criteria such as biocompatibility, maximum strain, environmental robustness and cost. As will be demonstrated later, the response of the particular DEAP materials used were highly linear and so allowed us to work at strain behaviour(in the form of a capacitance output signal that allowed us to infer a linear displacement) for the range

$$L(x) + 0.1L(x) \text{ to } L(x) + 0.9 L(x) \quad \text{where } L(x) \text{ is initial length of DEAP sensor} \quad (1)$$

Below, how we used the sensors and the outputs are described in more detail.

Demonstrator: Thoracic Motion and Volume Sensor for Respiratory Monitoring

The aim of the demonstrator was to align the DEAP sensors to the outside of the body to tell us what is going on inside the body. Both Lycra and the stretch sensors have ideal softness and compliance for interaction with the human body [9]. The sensors behave as variable capacitors and to measure their capacitance at any given time, and under any given load, a number of methods were used. To get usable readings from the sensors, custom circuitry and software was produced to measure and interpret the data. The range of the sensors is typically between $10e-12$ F to $10e-9$ F; therefore a capacitance meter able to measure down to 90pF was required. Firstly we tested a UNI-T desktop multimeter, secondly a self-solder capacitance

measuring printed circuit board from Sparkfun Electronics and thirdly an ATmega328pu microprocessor in the form of an arduino uno board. This board was used, with the addition of an external resistor and capacitor of known values, to create a basic RC circuit with a low pass filter. Using this circuit, and the following equation;

$$c = (2 \pi f)^{-0.5} \times [(V_i / V_o)^2 - 1]^{-0.5} \quad (2)$$

C= capacitance (Farads), f= frequency (Hz), Vi = voltage in, Vo=voltage out (Volts)

it was possible to derive the capacitance of the sensor accurately. It is important to note here that the capacitance of the sensor was being inferred rather than directly measured. The values actually being received from the sensor into the Arduino were changes in voltage. These voltage changes were then used to calculate the capacitance. As a result, there may be minor inaccuracies due to measurement error in terms of the minimum values able to be detected, but these were shown to be small enough as to be negligible in relation to the calculated readings. For each of the tests performed, it was shown that the DEAP sensor had a linear response. The third method for data collection proved to be most successful for gathering real time results in large numbers and had the additional benefit of the information being instantly plotted on a line graph.

Integrating the Sensors with the Vest

To enable individual readings from each sensor ribbon an anchoring system was developed to stabilise the end points and isolate the deformation. The specific length required for each sensor necessitated a bespoke, made to fit sensor for each measuring area, the design of which enabled the sensor ribbons to be slightly under strain when placed on the vest, allowing the sensor to work at maximum efficiency (see Figure 1). The positioning of the sensor ribbons for the initial testing are Shoulder Sensor, 1, Upper Chest Sensor, 2, Lower Chest Sensor, 3 and Lower Rib Sensor 4 (see Figure 2).



Figure1: Handcrafting bespoke sensors Figure 2: Positioning the sensors

Data Collection & Results

The vest is worn by the wearer. One at a time each sensor ribbon is placed on its set anchor points, secured and connected to the laptop. Once the wearer is connected a live reading is taken. The wearer is asked to undertake a number of tasks, such as shallow breathing, deep breathing, normal breathing, inhale and hold, exhale and hold, swallowing and chewing to

stimulate different breathing patterns. The wearer is asked to perform each task twice, resting for 1 minute between each task to regulate breathing. Every task is video recorded and the live graph readings are video recorded with sound. The sensor ribbon is removed. The same sequence of tasks is then repeated for each sensor ribbon on its set position and recordings taken (see Figures 3 and 4). An Arduino pro mini was used due to its reduced size; however the ATmega processor and external components remained the same as the third method for data collection.

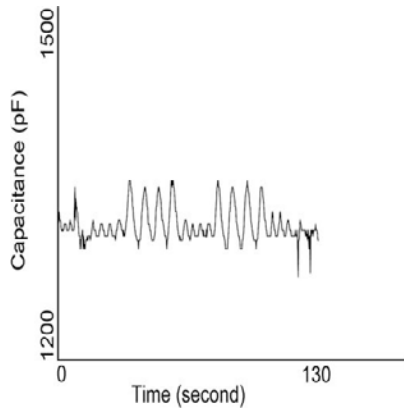


Figure 3: Deep breathing using lower rib sensor

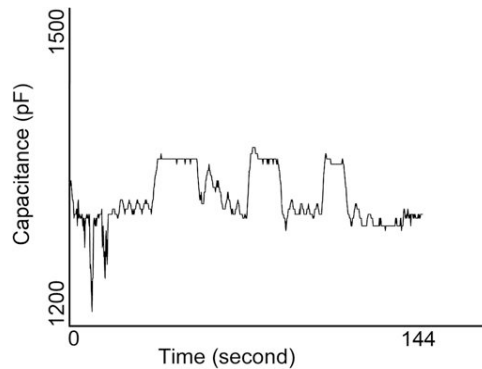


Figure 4: Inhale and hold using lower rib sensor

DISCUSSION:

The embryonic prototype demonstrates that there is significant scope for DEAP, ‘soft’ technology in human centred design applications for assistive healthcare and could support a sensing platform. Materiality and physical forms require careful consideration when designing products for on-body and real time monitoring. Devices and systems need to be as unobtrusive as possible. Materials that are soft, stretchable and conformable such as elastomers offer promising opportunities for accurate and unobtrusive body mapping in real time. We demonstrate the use of elastomeric sensors as a valuable tool for dynamically mapping the physical self. The thoracic sensor vest is an example of an intuitive, unconsciously interactive mapping tool aligned to the outside of the body to tell us what is going on inside the body.

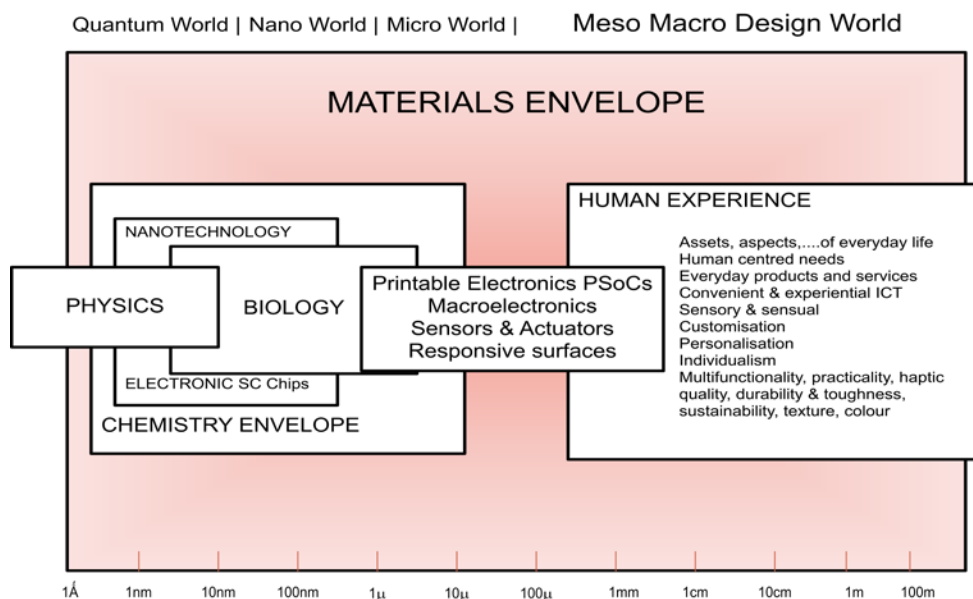
For expediency and deadline constraints we used a physical connection between the sensor and the computer, but envisage a wireless connection. We recorded markedly different patterns for each of the different breathing movements, two of which are shown, (see Figures 4 and 5) and suggests that with further work, particularly on the cross correlating the breathing movements data with volume change data, the stretch sensors could potentially be used for sensitive measuring of volume changes within the lung and that would allow an understanding of both the breathing rate and the capacity simultaneously and unobtrusively in real time [9, 10, 13].

BRIDGING CREATIVE DESIGN AND INNOVATION IN MATERIAL SYSTEMS:

Below is a multi-length scale map to enable us to create bridge from a fundamental Materials and Chemistry envelope to human experience and behavioural needs - in other words, how to bridge the nano-micro to macroscale physical regime that we as humans experience and live with everyday. Figure 5 below summarises this and highlights from a Design: STEM

Integration perspective, the key elements of early 21st century materials innovation from printable electronics, biocompatible materials, sensors and sensing to stretchable and responsive, non-intrusive surfaces. In particular, stimuli responsive polymers & gels have now been identified to provide the basis for significant re-use and re-function of material systems.

Figure 5: The STEM: Design Materials Bridge



RESPONSIVE MATERIALS:

The common feature in all cases with these material systems is a nonlinear change in properties or behaviour as the result of an external or environmental stimulus. The material response can range from a simple change in conformation, ionization or scattering state, through to phase transitions, bulk aggregation or complete dissolution. As a consequence, sensing and actuation are the most investigated functions of these materials. Application spaces include drug or therapeutic delivery, ‘smart’ surfaces and intelligent packaging. Materials that change their properties in a discontinuous or nonlinear response to a signal or change in environment are of increasing interest in a great variety of ways. Such materials range from inorganic solids to organic polymers and supramolecular assemblies.

A starting point is the interest due to intrinsically dynamic properties of responsive materials, which enables the interconversion of energies to do work, for example, by charging chemical potential into kinetic energy. Natural ‘soft’ materials perform this task very well, and so many studies have sought to exploit biological or biomimetic responses in order to generate signals, forces or motion. Much of the interaction that a material has with its environment is governed by its surface and modulation of the material’s surface characteristics can vastly broaden its range of application [14].

Can surfaces of materials be tailored to achieve specific changes in their responses to external stimuli? Can combining different classes of materials such as polymers, metals, porous materials and magnetic materials with a responsive surface present unique opportunities?

The most commonly attributed external stimuli are temperature, pH and light and these, as well as electrical stimulation used in conjunction with conductive polymers, has shown rapid progress in the creation of implementable applications.

Concepts Relevant to Environmentally Responsive Polymers and Gels

The most extensively studied stimuli responsive polymer is poly(N-isopropylacrylamide) or poly(NiPAAm). Poly(NiPAAm) is a thermoresponsive polymer. The unique feature of thermoresponsive polymers is the presence of a critical solution temperature at which the polymer undergoes a reversible phase transition. Poly(NiPAAm) is hydrophilic at temperatures below its critical solution temperature (LCST) of $\sim 32^{\circ}\text{C}$ in water. At higher temperatures, it undergoes a 'coil to globule' transition, resulting in a hydrophobic state. The LCST can be manipulated through the preparation of co-polymers and a value around the body temperature (37°C) and hence well suited therefore for biomedical applications.

The next most investigated stimuli responsive surfaces are those that respond to changes in pH. Variations in pH result in a change of the transition state, which can lead to a conformational change in the polymer and also affect ionic interactions with other molecules. Poly (acrylic acid) PAAc and poly (methacrylic acid) PMAAc which are weak polyacids with ionisable carboxyl groups are the most commonly used pH responsive polymers. These polyacids accept protons at low pH and release protons at neutral and high pH. When the ionisable groups are protonated, the electrostatic repulsion forces diminish within the polymer network.

Conversely, these materials transform into polyelectrolytes at higher pH with electrostatic repulsion forces between the molecular chains. These electrostatic interactions, along with hydrophobic interaction, govern precipitation/solubilisation of the molecular chains, deswelling/swelling behaviour and the hydrophobic/hydrophilic characteristics of the polyacids present. Further potential applications lie in their use as a form of shape memory gels. It is worth noting as well that there is also great potential through natural material hydrogel variants which are also soft as well as biocompatible [15, 16].

FABRICATION TOOLS AND METHODS:

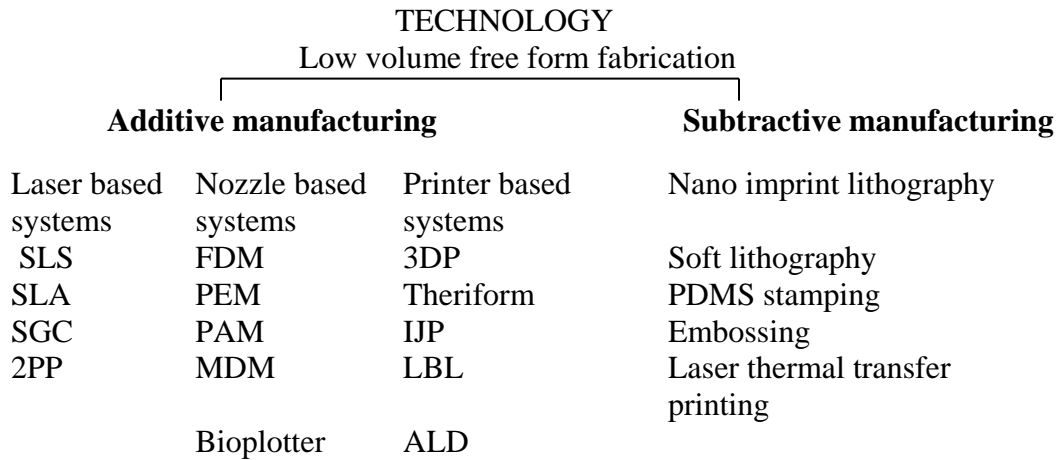
In order to create both the effect and the practical implementation of such performance characteristics however, we need appropriate fabrications & processing tools that are compatible with 'soft' responsive stretchable polymeric and gel base systems. The range of emerging as well as tried and tested process and product fabrication tool is wide and allows an assessment of scalability either through scale-up or probably through scale-out or multi replication. Table A below outlines many of the main fabrication routes and Table B (i) and (ii) summarises in a little more detail some of the most readily available and proven systems that will allow the advantages of 'soft' technology to be preserved at a range of length scales [17, 18, 21]

Table A: The main fabrication routes:

FABRICATION TECHNOLOGIES				
Conventional Processing Technologies	Additive Mfng Methodologies		Molecular Assembly	Learning from Nature
	Small Area High Res ⁿ IJP	Larger Area Lower Res ⁿ IJP	Colloid Process Technology	
Crystallisation/Precipitation	Nano Imprint Lithography	Screen Printing	Polymer Phase separation	Biomimetics
Polymerisation	LTPP	Web Printing	Surfactant & BCP Templating	Dendrimers
Emulsification	Soft Lithography	3DPrinting	ALD	Inverse Micelles
Extrusion	PDMS stamping		'SAM / DAM'	Enzymatic / bacterial Fermentation
Electrospinning	Embossing	Rapid Mfng		
	(10-100nm)	(5-1000nm)	(1-100µm)	(10-1000nm)



Table B: Additive manufacturing technologies for 'soft' product fabrication:



KEY:

- | | | | |
|-----|------------------------------|------------|----------------------------------|
| SLS | Selective Laser Switching | MDM | Multinozzle Deposition Modelling |
| SLA | Stereo Lithography | Bioplotter | Bio Extrusion Processing |
| SGC | Solid Ground Curving | 3DP | 3D Printer Printing |
| 2PP | Two Photon Polymerisation | IJP | Drop on Demand Ink Jet Printing |
| FDM | Fused Deposition Modelling | LBL | Layer by Layer Printing |
| PEM | Precise Extrusion Mfr | ALD | Atomic Layer Deposition |
| PAM | Pressure Assist microsyringe | | |

FUNCTIONAL SURFACES AND INTERFACES:

Biomimetic and bio enabled materials science and engineering

In materials processing, Nature replaces the intensive use of energy with the use of information, which equates with structure at all levels, from molecules to ecosystems. Indeed, most of the exceptional functionality of biological materials is due to their complex structure, driven by their chemical composition and morphology derived from DNA. It is here that the most important aspect of biomimetics emerges, and it has the power to redesign engineered products and perhaps to remake the way we make everything in the future.

However, first we need to know if biology can provide us with a credible replacement for our current technologies, which are largely based on materials and materials processing going back perhaps one hundred years.

Materials Processing: Biology v's Technology

At lengthscales up to 1 cm, where most technology is situated, the most important variable for the technical solution of a problem is manipulation of energy – (up to 70% of all technical problems), followed closely by the usage of materials. Thus, faced with an engineering problem, the tendency is to achieve a solution by changing the amount or type of materials or changing (usually increasing) the overall energy requirement. In addition, while engineering commonly processes material by fabrication with attendant heat and mass requirements, biology uses rich, embedded molecular information (composition, arrangement of components, molecular size/shape, hydrophobicity, charge) to direct net forming and even actuation through growth and assembly processes, since in biology the most important variables for the solution of problems at these scales are [Information and Structure] rather than [Energy and Materials].

Biomimetics as implementable actions

By combining the degree of freedom of hierarchical structuring, inspired by biology with the variety of materials offered by chemistry and engineering, there is a huge potential to obtain new or unusual combinations of material functions/properties by structuring a given material rather than by changing its chemical composition for example. This allows the possibility of both a Design and a STEM approach to the creation of useful performance characteristics associated with a 'soft' technological approach. The advantages of hierarchy- greater versatility in production and properties, in particular the separate manipulation of fracture toughness and stiffness however have still not been fully realized.

Much of nanotechnology relies on self assembly, yet self assembly is really only needed at the lowest size level. After that, there are other techniques available such as electrospinning, surface templating relying on shapes and chemical bonding familiar in polymer physics and processing. Such techniques of assisted self assembly overcome a major criticism of self assembly in general: that it takes too much time and occurs at too small a scale [19]. With enhancement provided by an enabling fabrication change such as additive manufacturing, this is no longer an issue and directed assembly of materials becomes one of the paths to the creation of new material product systems. Soft biological systems restricted to ambient conditions of pressure and temperature, mean that the development of manufacturing technologies for

biomimetically inspired material products will be a major research topic in the foreseeable future [20].

CHALLENGES FACING THE MATERIALS INDUSTRY:

In all of the above, we have discussed applied research, development and demonstrable material possibilities (R, D & d). The reality over the next decade will, in our view, be based on a significant shift to an ability to take Bio-Nano-Info-Cogno science fundamentals at the nano-micro scale and to create the meso to macro fabrication processes which enable and enhance the intrinsic properties of synthesised or natural materials at the macro scale that is useful and beneficial in aspects, assets and phases of everyday life. However, creating the critical material skills base that can be coupled to creative design expertise will be the vital game changer [17, 18].

An example of prudence here is the current praise heaped upon so called '3D Printing'. The more useful term is Additive Manufacturing which is much less restrictive as it describes some 20 fabrication methods and tools whereas 3D printers utilise only 2-3 methodologies and these are further restricted by the paucity of synthetic polymeric materials that exhibit appropriate thermo-physical properties.

If digital manufacturing has to therefore address new, 'soft' stretchable materials, new CAD programming methods suitable for genuine curvilinear fabrication and the increasingly significant role of evolutionary design through the application of biomimetic approaches to the creation of both aesthetic and functionally useful products [20]

CONCLUSIONS:

A creative design: Innovative Material Science approach is considered to be a prerequisite requirement now to remain at the leading edge of new useful products and services design. Applied Materials Science and Engineering, coupled to design interaction will allow the development of new approaches to 'soft' technology. When coupled to craft and making skills integrated into materials science and innovations in fabrication, a new paradigm shift for human centred, purposeful technologies will be possible.[20,22]

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