Bioengineered Textiles and Nonwovens – The Convergence of Bio-miniaturisation and Electroactive Conductive Polymers for Assistive Healthcare, Portable Power and Design-led Wearable Technology

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Abstract: Today, there is an opportunity to bring together creative design activities to exploit the responsive and adaptive 'smart' materials that are a result of rapid development in electro, photo active polymers or OFEDs (organic thin film electronic devices), bio-responsive hydrogels, integrated into MEMS/NEMS devices and systems respectively. Some of these integrated systems are summarised in this paper, highlighting their use to create enhanced functionality in textiles, fabrics and non-woven large area thin films. By understanding the characteristics and properties of OFEDs and bio polymers and how they can be transformed into implementable physical forms, innovative products and services can be developed, with wide implications. The paper outlines some of these opportunities and applications, in particular, an ambient living platform, dealing with human centred needs, of people at work, people at home and people at play. The innovative design affords the accelerated development of intelligent materials (interactive, responsive and adaptive) for a new product & service design landscape, encompassing assistive healthcare (smart bandages and digital theranostics), ambient living, renewable energy (organic PV and solar textiles), interactive consumer products, interactive personal & beauty care (e-Scent) and a more intelligent built environment.

Keywords: Textiles, non-wovens, electroactive polymers, responsive hydrogels, microfluidics, fashion design, printing.

1. Introduction

The emergence of novel materials with advanced functional features, similar in provision to the equivalence of low performing silicon logic & memory, over the next 3 to 7 years, will enable us to almost completely renew our perceived use of textiles, fabrics and polymer surfaces, in a range of human centred applications. In particular, the enabling process integration will be afforded by printable sensors, detectors and delivery systems. These are the technological kernel of ambient life systems – and also include the ultra large area solar cells (portable power) and printable light. New material properties and characteristics will allow designers flexibility in how to 'imagineer' and implement products, devices & integrated systems, functional and beautiful, improving our quality of life. This can only happen, if the new materials world integrates with the innovative design world, opening up new product functionalities and options. Historically, it is worth considering how & why this could occur and is it capable of significant acceleration in the future. The development of the physico-chemical and aesthetic properties of materials used to be collaboration between the arts and sciences. The potential benefits for renewing / reviving such a vibrant culture are great, in particular, the unifying concept of ambient life applications, with the 'citizen at the centre' of functional, beneficial technology [1,2].

The materials problems of the cultural industries, typically concerning a combination of cultural, sensory, environmental, performance and communication characteristics and properties, are crucial to the growth of these industries and intellectually demanding, for example: materials for 'intelligent walls or polyvalent surfaces' that can modify their properties through sensing human interactions & emotions [3].

From materials in the form of 'dots, lines and surfaces' to fabrics, textiles, assistive healthcare products, renewal energy and an interactive and intelligent built environment, we will see a revolution in the use of flexible, lightweight responsive and even emotionally responding materials created by the everyday tools of the creative product designer. Beyond this will be 3D supramolecular structures and macro

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structures, created through self assembly and rapid prototyping respectively, especially when created with semi-conductive polymers with high mobility and with some degree of reasoning. The key to this emergence of useful intelligent surfaces is four fold [4]:

i. New electro / photo / bioactive functional materials;
ii. Familiar physical form transformations;
iii. Free form experimentation;
iv. MEMS integration into 'sense-analyse-actuate-deliver' systems and devices.

2. The Rise of Intelligent Materials

Conjugated, conductive polymers were discovered in the late 70's by Heeger et al. Shortly after this, light emitting polymers were developed at the University of Cambridge by Prof. Friend et al. These two materials events, due to the interest in material properties at the micro and nano scale, have given rise to a functional materials revolution to equal microelectronics and biotechnology (Figures. 1 and 2).

3. OFED Functionality in New Materials and their Processing Technology

OFEDs are a genuine attempt at using a molecular engineering approach to create a renewable energy platform. Achieving low cost manufacturing is essential to ensure maximum penetration of OFED technology into general power applications. Solution processed OFEDs attract, as it is now possible to envision a high throughput R2R printing process or R2R multilayer, thin film co-extrusion process which can make large area OFEDs at low cost. Possible techniques for relatively large pixel (low definition) printing are screen, gravure or flexography. Nevertheless, even with ultra low cost printing of the organic layers of the OFED device, high device performance typically still requires integration with one or more high vacuum process steps for electrode formation during device manufacture. This adds complexity and reduces throughput relative to a pure printing or deposition process and hence limits the ultimate low cost potential. It is thus highly desirable to develop an OFED manufacturing process that does not ultimately require any vacuum process steps.

The heart of the design paradigm for solution processable OFEDs technology lies therefore in adding as much functionality as possible into the active organic materials and then to use these materials in device structures with as few active layers as possible, in contrast to vapour phase processing strategies which has progressed by exploiting multi layer device designs with simpler small molecule materials. Scaling solution processable technology for large area organic power will need the development of new solution based processes of materials specifically optimized to improve inherent adhesion between the organic active layers at lamination interfaces. How to do this systematically requires a deep knowledge of the behaviour and characteristics of both polymeric and small molecule organic semiconductors [5].

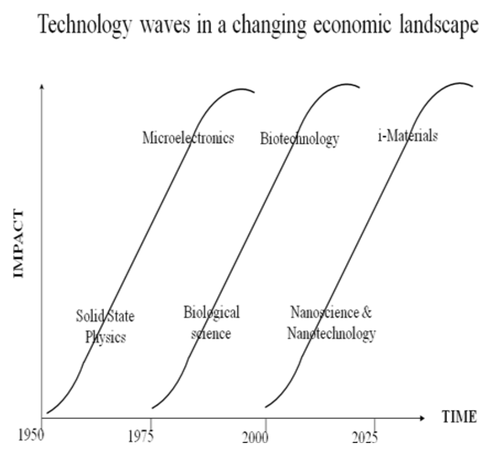

Figure 1 Technology waves in changing economic landscape.

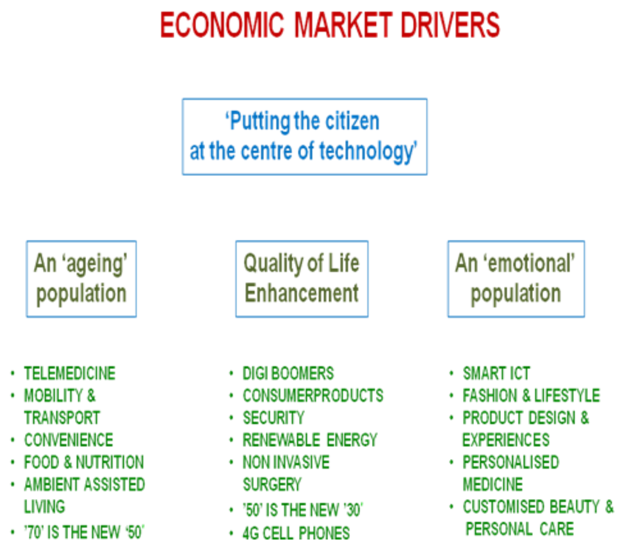

Figure 2 21st century economic market drivers.

3.1. Polymeric and Small Molecule Active Organic Semi-conductors

Both have material routes to functionality; both have strengths and weaknesses especially when it comes to implementable printing, deposition or coating methodologies.

Small Molecules: Higher mobilities generally than polymers μ~0.5cm^2/Vsec cf μ ~ 0.1cm^2/Vsec and have higher stability but reproducibility and reliability are challenging. They have a wide range of solubilities and this can make fabrication of multi layer (multi soluble) structures also challenging.

Polymer SC's: Lower mobility (η_p ~ 0.02 - 0.10 cm^2/Vsec) but, due to their narrower (limited) range of solubilities, can be more readily processed and fabricated into multi layer and, due to their favourable rheological characteristics, tend to yield good uniformity of performance.

State-of-the-Art is P3HT (photosensitive polymer) and the focal point will be the search for suitable (higher performance) low band gap materials with a charge mobility μ_p in the range 0.1-1.0 cm^2 /Vsec and light absorption spanning the 400-900 nm range of the EM spectrum. This allows for example, the use of photovoltaic material surfaces indoors as well as solid state printable lighting and hence the freedom to create novel product designs (for example, solar textile tapes).

Solution based co-polymer structures of LUMO and HUMO materials are the preferred active layer. In parallel with laboratory development the processes for large scale production are being developed. The aim will be to have in-line large area roll to roll processes with no vacuum processing. Two alternatives for the deposition and patterning of the active layers are in-line printing which requires significant innovation in tooling and materials. The alternative approach is to use multi-layer thin film polymer co-extrusion processing developed by the photographic industry over the last twenty years to be a proven reliable, cost effective manufacturing technique [6,7].

3.2 From Laboratory to Implementable Fabrication

By introducing new conformable material functionality, we now enter a period in which 'lab to fab' technologies emerge where materials which have been synthesised and characterised in very small quantities will become semi-industrial with sufficient amounts of material to allow for demonstrable product design & device function. In addition, dots, lines, surfaces and 3D structures are now possible, through IJ printing, fibre spinning, screen printing very large area films, embossing and multilayer, thin film extrusion techniques. The reason for these developments is due to the fact that many of the new functional materials are organic and, in fact, are solution processable. As mentioned previously, the classes of material which are becoming available are derivatives of the original discoveries made by Heeger et al in the late 70's based on conjugated, conductive polymers [8] and by Friend et al in the early 1980's based on light emitting polymers [9] - in other words, conformable, lightweight, transparent electro and photo active polymeric and to a lesser extent, small molecule organic materials. When we couple these to:

a) Creative design principles and techniques and,
b) Convenient human benefits through medicine, transport, shelter, energy, information and communication and lifestyle.

then we can create both a needs driven and market driven set of product opportunities which will act to accelerate the investigation and implementation of processes to make advantageous basic materials as well as the technologies to enable them to be used at the most economical cost frameworks while providing surprising and/or desirable functionality or experience. We can summarise these connections as shown in Figures. 3, 4 and 5:

Materials (evolutionary) developments in the near future

1. Electroactive Polymers
2. Photoactive Polymers
3. Bio Responsive Hydrogels
4. Electro Luminescent Fibres & Films
5. Photovoltaic Fibres & Films
6. Photonic Fibres & Films
7. Biomimetic Materials
8. Meta Materials (counter-intuitive effects)

Existing materials already in development

9. Shape changing materials (SMAs,SMPs)
10. Colour & optically changing materials (chromics)
11. Energy exchanging 'smart' materials
12. Materials exchanging 'smart' materials

Figure 3 Materials (evolutionary developments in the near future.

4. Design Led, Needs Driven, Materials Anchored solutions

Design is an important gateway to new products and services leading to competitive advantage and commercial success, in terms of 'materials' and, there are two essential layers to the design process.

The first is the investigation, exploration and exploitation of opinion / emotive / sensory effects and values of materials without defined product identification. This is the initial step to product design. The more sophisticated and advanced the results at this stage - the more varied are the product possibilities and the more sophisticated is the product (sophistication does not always equal complexity). In the case of textiles, the key role of the designer has issues of touch, handling, flexibility, drape, colour, weight, texture, pattern and appearance to explore and maximise variables through experimentation. This results in the widest choice / range of the 'feeling' properties of materials. This work is not driven by theory, but by testing and extending the known boundaries of existing material behaviour. The approach is necessarily experimental, exploring the unknown, exploiting by mistake, where failure is as important as success. Much more textile material is needed at this experimental stage than is contained within the selected, edited results. This is a key driver for any innovative product technology development. If we use the same approach for exploring textiles with new conformable materials and technologies, we will have the widest possible choice of the 'feelings' properties of these sophisticated 'dots, lines and surfaces' with which to develop cutting edge products concepts based around emotive value and human centred thinking. Beyond this, however, lies the relatively unexplored territory of responsive, adaptive and interactive materials containing some intelligence, based on the integration of semi-conductive materials with high mobility and micro electromechanical systems development, for example.

The second stage of design is the development of such characteristics into well defined application and product. Just as it is important for the two sides of the materials community to communicate and influence, so it is for the two design stages - for instance, the textile and the fashion designer working together, or the textile and the vehicle designer or the consumer product designer working together. This interdisciplinary approach can be best achieved through an 'Open Innovation Centre' concept, in which design & materials integration can be seen through consumer needs, market drivers and industrial co-development. This approach pushes the envelope of products and services with a range of research capabilities that no single industrial partner, for example, would be able to duplicate [10].

4.1. Dots, Lines, Surfaces and 3D Structures

A major benefit, which impacts the uptake of OFED's, is the fact that many of the 'active' materials can be synthesised in the form of polymeric and gel solutions. This flexibility, when coupled to a phase transformation such as a chemical reaction, a cross linkage step, a solidification, a drying or a curing step, allow the transition of bulk fluid to controllable physical forms i.e.

a) Droplet and spray production ('dots');
b) Fibre spinning & material phase transformation ('lines');
c) Thin film, multilayer extrusion & deposition ('surfaces');
d) Rapid Prototyping - 3D printing & injection moulding ('structures').

In turn, these methodologies allow designers to create both the desired 2D & 3 D materials and to experiment with multiple composite forms, previously untried, if given ample quantities of material.

'Dots' translate to planar, sheet to sheet printing, using DoD ink jet for small & large area applications.

'Lines' translate to fibres, for weaving, knitting, sewing and embroidery, for relatively large area applications.

'Surfaces' translate to large area screen printing, reel to reel web based printing and multilayer, thin film extrusion for very large area applications and the crossover to 3D supramolecular objects, which can be fashioned digitally, through Rapid Prototyping.

Beyond these are 3D structures created by self & directed assembly or organisation and macroscopic rapid prototyping. This variety and flexibility will accelerate the rate of 'active' polymer material science uptake and implementation into the creative industries. With such a range of new materials' functionality and mechanical flexibility & conformability, it is appropriate to think of a needs & market driven scenario, with the 'human at the centre' i.e. Who am I? Where am I? How am I? Can I?

In this way, we can address both societal and commercial aspects of product and service design, made with purpose and designed for function and exploiting the characteristics of the new materials, to create aesthetic and emotive values.

Textiles have a relationship with many other disciplines and through some of these interdisciplinary relationships, innovative results feed back into 'in-body', 'on-body', 'around-body' interventions. Textiles have significant benefits which can be realised both societally and commercially. They are conformable and versatile, with adaptability, portability, washability; and as such, are uniquely placed to partner and integrate with other materials attributes to create smarter materials for healthcare, energy, consumer goods and intelligent built environment. The boundaries between therapeutics, assistive healthcare monitoring and fashion will blur, for example, as bandages become more like clothing and clothing integrates sensing, diagnostics and active ingredient delivery capabilities e.g. drug delivery for healthcare, fragrance delivery for personal care and vitality.

This paper is the beginning of an exploration of the collaborative roles of creative industries with emerging new materials and technologies in order to define and elaborate on the future landscape of product design, with particular reference to science convergence in biology, polymers & electronics and the parallel emergence of ambient life applications in healthcare, textiles & fashion, interactive consumer products and intelligent buildings.

4.2 Examples of Materials to Healthcare, Energy and Wearable Technology

The convergence of Bio, Nano, Info, Cogno technologies with Textiles, Polymers and Electronics integrated through processes incorporating dots, lines, surfaces and 3D structures is shown in Figure 4.

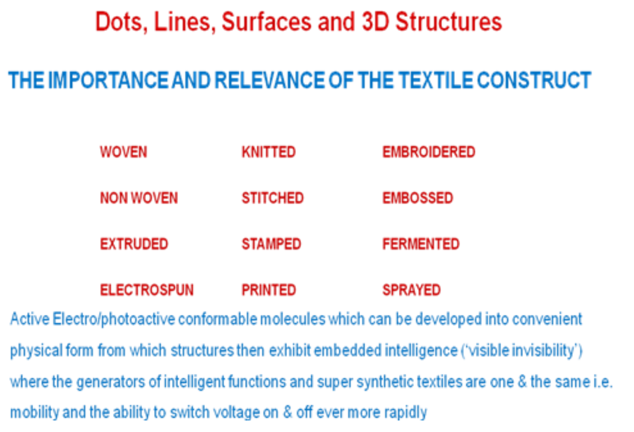

Figure 4 Dots, lines, surfaces and 3D structures.

Examples, of opportunities and practical applications and how they will ensue initially, are as follows:

On body applications:

- Clothes & Fashion
  - Light, sound, sensory effects in location / mood context
- Healthcare
  - Point of care diagnostics based on bio sensors in clothing. Patient care-chronic wound monitoring, therapeutic response and data reading & analysis (e.g. 'smart' bandage concept).
- Personal care / Beauty care
  - Controlled release materials with smart environmental triggers for sensory, body temperature and antibacterial benefit (e.g. e-scent concept of wearable technology).

Around body applications:

- Transportation
  - Organic, pixelated lighting, controlled by the driver's and passenger's state of tiredness, need for information etc. Bio sensing of both people and environment integrated through sensory responsive hydrogels.
- Built environment
  - Smart furniture, interior walls, carpets and curtains, draperies, will provide information on an individual basis, using RFID / Bluetooth signalling and large area ultralow cost sensor driveways (e.g. intelligent materials-interactive surface concepts). Smart health sensing, for both inhabitants and the fabric, of the living space.
- Renewable energy
  - Large area portable (power) storage and hence low cost heating and lighting into off grid living environments (e.g. organic or plastic solar cells concept).

4.3 Ambient Assisted Living Platform

Other applications will include consumer electronics, printable light surfaces, entertainment, infotainment and architainment, furniture, toys and games, telecoms and interactive consumer goods and services. In an ambient life platform, encompassing biology, digital systems, miniaturisation and nanotechnology, it will be the integration of these systems based on novel materials and explorative design, which ultimately controls the degree of successful implementation (Figure 5).

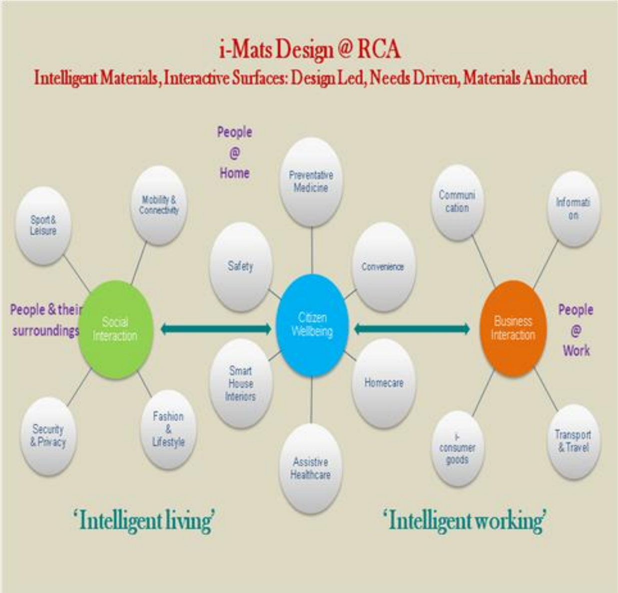

Figure 5 Intelligent materials, interactive surfaces.

5. The Convergence of Biology, Electronics and Polymers and the Impact on Product Development in the Preventative Medicine and Medical Device Design

In the past twenty years, there has been a growing interest worldwide in bio-interactive materials for medical applications. This research activity has supported the emerging field of tissue engineering and drug / device combinations and, most recently, applications in molecular medicine, such as protein, cell and gene therapy.

Five key bio-compatible material innovations:

1) Surface / Interface modifications
2) Drug / Active Materials Delivery device combinations
3) New materials discovery
4) Tissue engineering
5) On-body/Around-body responsive sensing

5.1 InfoTech+Biotech Convergence with Design and Embedded Sensing=Transformation in Healthcare (Assistive Technologies and 'smart'Bandages)

It is now evident that the building blocks of 21st century materials innovation are already in place. Four major areas of advancement i.e. information technology, biotechnology, nanotechnology and neural networks are converging to create a host of new opportunities in biomedical materials, where binary code (0's & 1's) are now being replaced by A, T, C & G (DNA code).

The architecture of communication systems can be seen as very similar to that of the human nervous system. As biomaterials research progresses over the next two decades, several areas of development will push the frontiers of medical innovation. Nanotechnology and sensors top the list. Next is biomimetics, the ability to use materials to mimic the ways in which nature manages materials within the body. Fourth on the list are environmentally responsive materials, responding to a stimulus from outside, such as temperature, light, electricity, pH etc (Figure 6).

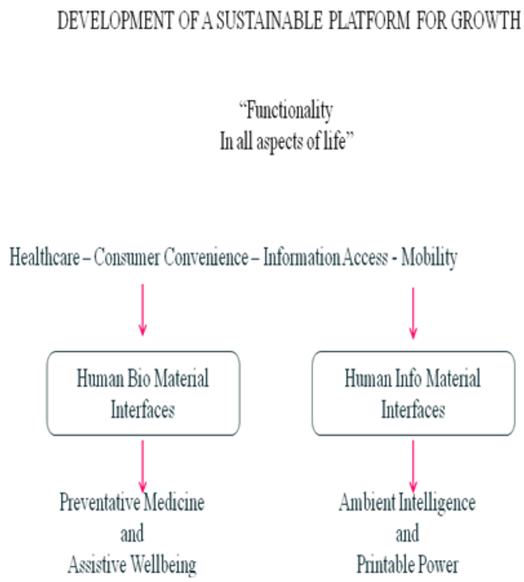

Figure 6 Development of a sustainable platform for growth.

5.2 Printable and Processable Integration of Nanostructured Chemo-optical Responsive Gels with Electroactive Polymers

The final area is biodegradable materials. Over the next two decades, two of the largest driving forces in biomaterials research and implementation will be biotechnology and information technology. The biotech revolution is already afoot. Today, there are many clinical studies underway in gene therapy and stem cell biology. These, and other biological therapies, will very likely include some form of device that will be used to deliver, house, protect or monitor the therapy being applied. Sensors and actuators have become vital to medical developments from an information standpoint. To help manage patients' diseases and illness, physicians and researchers need to gather a variety of physiological data. Such physiological measurements have to be converted quickly into electrical signals, which in turn can be captured, analysed and stored as data, transmitted outside the body for further analysis and interpretation. These two trends, the growth of infotech and biotech, will transform traditional medical technologies and the results will revolutionise healthcare.

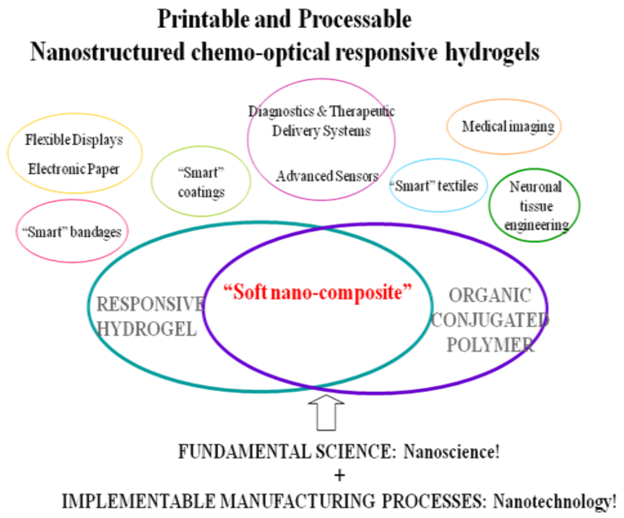

Figure 7 Nanostructured chemo-optical responsive hydrogels.

Today, much of the healthcare is about treating a disease or other medical problem - once a patient acquires it – palliative medicine, which improves quality of life, but rarely cures the disease. The future healthcare is to be about prevention and possibly the curing of the diseases. As material sciences progress along with science in general, biology will emerge as a critical force. Biology, together with material and engineering science, will result in better solutions for the myriad of acute and chronic diseases that we face in the world. An example of work in progress is the development of 'smart' bandages.

5.3 'Smart' Textile Bandage Device Development (Example I)

The aim of this work is to design, develop, trial and ultimately take to market the next generation of smart therapeutic textile based bandages that will enable the realization of highly patient-centric healthcare and significantly reduce healthcare costs. Figure 8 illustrates the layers and components comprising the bandage. It will not only protect the wound and sustain a healing environment but through the use of nanoscalar and nanostructure biopolymer composites actively enhance healing by controlling the delivery of therapeutics in response to physiological data gathered by an array of smart biosensors covering the wound's surface. Through the use of wireless broadband connectivity, clinicians will be able to monitor in real-time the patient's recovery and if appropriate to remotely intervene and control the device. Clinicians would be alerted at an early stage of any severe changes threatening the patient's wellbeing. The design of the device will enable patients to easily replace the inner disposable therapeutic layer, taking into consideration patient mobility and disability situations. In addition, skin conductivity sensors will monitor patient stress and anxiety in order to gauge over all comfort and wellbeing.

The focus of this concept then is the development of smart textile bandages on responsive hydrogel materials, where diagnosis and smart drug delivery (theranostic) functions are embedded and fully integrated. This will be achieved by the incorporation of bioactive molecules within smart delivery devices present in the bandage (nanocomposite that comprises disperse stimuli responsive polymeric nanoparticles within biocompatible matrix made of hydrogels attached to a textile construct) together with miniaturised electronic biosensors and optoelectronic sensors in the bandage that will be based on composite hydrogel electroactive materials technology. A complete device demonstrator, also including a system for signal processing and clinical software, will be assembled and tested for clinical validation through a series of prototypes, culminating in a final demonstrator technology, yielding cost, performance and comfort data.

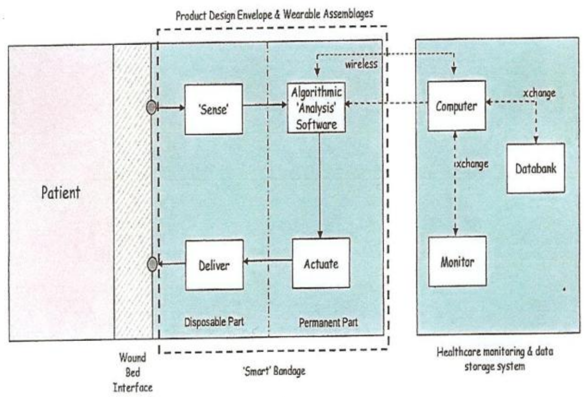

Figure 8 Smart bandage concept (schematic).

5.4 Organic Large Area Photovoltaics

The vision is that of Smalley i.e. towards Terawatt renewable energies by solar harvesting delivered at the lowest possible cost. So-called thin film technologies are slowly but steadily replacing amorphous-Si and polycrystalline-Si. Thin films allow for the production of very large areas for harvesting sunlight and this is necessary when considering giga watt production. The initial systems are CIGS, CdTe and DSSC and are in development. However, a persistent disadvantage is the use of heavy, rigid and expensive glass plates to hold the thin film modules. The lower glass sheet acts as a substrate, the upper sheet serves as a barrier to moisture, oxygen, is scratch resistant, while maintaining good transparency. Such an installation therefore requires a solid subconstruction, with the installation cost accounting for at least one third of the total cost. The obvious next steps therefore are thin film devices which are lightweight, flexible, conformable and have significantly reduced installation costs. In that context, the two topics for development are:

i) Organic or plastic photovoltaic 'wallpaper' and
ii) Solar textiles where thin film tapes are integrated into curtains, drapes and external fabric applications, such as awnings etc.

5.5 Organic Photovoltaic Cells (OPVs) and Solar Textiles (Example II)

OPV constitutes an ideal example of large area, low cost electronics using organic materials. The area is certainly large! Even at 10% efficiency, 10^8 m^2/ann would be required to produce ≥10GW/ann. This is still small compared to the 10^{12} m^2/ann of paper and the 10^{10} m^2/ann of polymeric thin films manufactured globally. Low cost is paramount! Unlike displays, where sensory appeal to customers is vital, all that counts with energy (power) is cost and reliability. Over the last three years, the knowledge gained, concerning electroactive and photoactive polymers, has resulted in technological advances in photo to electron conversion efficiency as well as materials design, which allows for infra red as well as the visible spectrum to be included in energy harvesting. By utilising polymers such as polyethylene terephthalate (PET) and nanostructured actives such as P3HT (poly (£-hexyul thiophene)) and a fullerene derivative PCBM (6, 6-phenyl C_6 butyne acid methyl ester), not only are acceptable level of efficiency being adhered, but the conformable nature of the system materials are allowed for more freedom of design resulting in concepts such as 'Soft House' shown in the Figure 9 below to be developed. Here photovoltaic tapes can be integrated into aesthetically excellent fabrics, which yield both portable heating power and solid state lighting power.

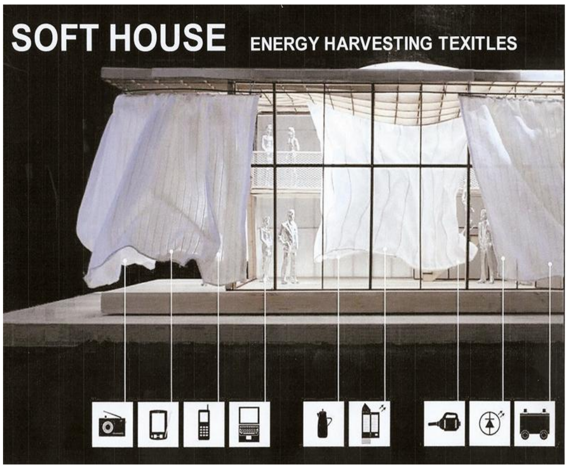

Figure 9 Portable solar textiles (M.I.T. Department of Architecture (2007).

6. Order at the Micro & Nanoscale

With synthetic materials we make use of fast and easy processing techniques in the melt, but until now these processing methods did not allow the ordering at the nanoscale that makes natural materials so unique. However, the first attempts in structure formation during processing (apart from crystallisation) have been made, making use of molecular recognition and self assembly. Nature is also perfect designer on the macroscopic level. At this moment, we are only able to simulate perfect structures with synthetic composites, using supercomputing. Nature seems to be able to reproduce these structures. The production of such structures with synthetic materials is still beyond present capabilities. We can exploit the great synergy between the fields of material sciences and life Sciences! Companies who master aspects of both fields might expect to gain competitive advantage. So we have to try to define opportunities in the overlapping domain. We have increasing practical use of real polymer electronics, which can fit almost invisibly into everyday objects, due to their lightness, flexibility and near transparency. Coupled to this is the ability now for designers to be able to freely experiment with these new materials and material systems, in order to create more human centred products. The final strand, then, is to bring these activities together in a form of tangible and effective convergence, a system incorporating ambient intelligence with designer friendly materials and manufacturing tools, which can be put together to create functional as well as beautiful products and services, but also can be created at relatively low cost and almost by 'on demand' needs. The key issue is to integrate nanotechnology, organic conductive polymers and innovative design engineering as early as possible in the conceptual stage, building up to implementable, scaleable technology.

It brings into sharp relief the concept of design with integrity, the ability to convey trust and to help convince the public that technology, when designed with the human at the centre, is valuable.

6.1 The Rise of Embedded Network Sensing (ENS) Combining printable Bio and Electrochemical Sensors and MEMS Device Vehicles

ENS has been developed initially for a range of scientific applications from terrestrial ecology to contaminant monitoring in the atmosphere to aquatic marine biology. More recently, photonic and electronic sensors have been developed and integrated into thin film technologies using micro electro mechanical systems (MEMS) vehicles. The acceleration of sensing & detecting miniaturised systems is being driven by their increasing use in interactive consumer products.

A key question we are addressing, however, is the potential to incorporate sensing technology with delivered effects based on active materials and miniaturisation which will enable textiles and fabrics to act as 'smart' or interactive / responsive surfaces. An initial example being e- Scent, described below.

6.2 Printed Bio and Electrochemical Sensors

Chemically and biologically stimulated sensors react to smell and taste senses, i.e. fragrances and flavours and have been developed recently, because of demands for real time monitoring in healthcare, environmental protection, the food industry and the personal care and lifestyle sectors. Recent advances in chemical and electrochemical sensing have been linked to the parallel discovery and development of new electroactive and photoactive polymers, solving the analytical techniques problem of low analyte concentration detection, poor selectivity and high detection time, giving new commercially available devices which are lighter, smaller and in many instances, almost transparent and flexible. The utilisation of electro, photo and bio active polymers therefore given the added dimension of printing, coating or deposition onto textile constructs and indeed, by creating 'active' fibres, the potential to create 'smart' sensing fabrics offer large areas of detection.

In active material detection terms, enzymes have been historically the most used and studied biological compounds in the design of biosensors and a wide range of them have been applied to specific healthcare needs and applications [11-18].

Beyond purified enzymes, a number of other bioactive materials lend themselves to particular application including creatinine, dopamine and DNA [19-23].

Printing technologies (Drop on demand Inkjet, screen printing, POMS stamping and web based roll to roll) allow these sensor technologies to be deposited onto thin nonwovens and plastic substrates, giving, as a consequence, low cost and easy to use devices. Moreover, the bio and chemical sensors and the active ingredient delivery system can easily be integrated onto the same conformable substrate. This enables the use of both sensing and controlled release, when suitable payload vehicles are incorporated, such as a MEMS reservoir (e-Scent example) or as a composite coating incorporating a responsive polymer or gel ('smart' textile bandage example). A new generation of pressure sensors have been developed, where a piezoresistive polymer film is used as sensor-detector and uses sensitive electrical resistance characteristics to trigger a response. These sensors contribute a new generation of pressure devices enabling monitoring and analysis over a large area on not only discrete points, i.e. Body Area Networks or BAN technology. Research groups such as CIDETEC in Spain have started to develop implementable sensor arrays using large area printed techniques to generate novel uses including security and safety applications as well as healthcare and lifestyle [24].

6.3 E-Scent Wearable Technology (Example III)

A new movement in functional "holistic" fashion, that incorporates sensory systems in design-led wearable technologies is 'eScent', which seeks to change the experience of fragrance to a more intimate communication of identity, by employing emerging technologies with the ancient art of perfumery, Aromachology (the science of fragrance) and the growing trend of complementary therapies.

eScent is a user-worn dispenser which offers the localised and non-invasive controlled-release delivery of precisely metered sensory ingredients in response to user-driven demand [5]. Triggered by an electrical signal through a built-in MEMS device, it can be embedded in jewellery and clothes to enable the controlled release of active ingredients such as fragrances, insect repellent, deodorant or bronchodilators, where you want it, when you need it, from a device the size of a small button. The aim is to go one step beyond passive sensory systems (such as traditional microencapsulated techniques), via the integration of wearable technologies in smart textiles that not only offer function to fashion, but are designed for psychological end benefit to reduce stress. The advantage of eScent is that it has the capability of targeting therapeutically established vapor-borne fragrance molecules as an atomized mist to specific parts of the body and in response to physiologically monitored stress response.

eScent exists at the cross-over of two main disciplines – the developing knowledge and utilisation of nanotechnology and ‘miniaturisation’, and the science of olfaction and how it affects the human brain and senses, allied with the vital role of aesthetically, intelligent design in creating market leading products – to create a unique product that is being developed in response to needs initially identified within the fragrance industry. With a current global market value of around £16bn, set to rise to £27bn by 2011, the fragrance industry is facing growing pressure to innovate, differentiate and to reflect growing trends in the consumer markets of choice and personalisation in order to increase profitability and market share. The second market opportunity identified lies within the health sector, where a continuing increase in the numbers of individuals suffering from mental health disorders is causing the NHS to seek complementary and proven alternative therapies and treatments; by 2020, according to World Health Organisation statistics, an estimated 1 in 4 of the UK population likely to be suffering from a mental disorder [25]. eScent works by using a microfluidic device to distribute fragrance directly into the immediate vicinity of the end user, upon a sensed stimuli or user instruction, forming a personal ‘scent bubble’. This product platform can offer the concept of multi-scent devices to both the fragrance industry, i.e. a designer *‘fragrance wardrobe’*, housed in elegantly designed garments (for example a Chanel suit) and available throughout the day/night, and to the healthcare sector, allowing a collection of mood enhancing scents i.e. lavender to relax, neroli to reduce anxiety or lemon to stimulate [26], to be contained in a small device held on the user, allowing early detection of stress and releasing appropriate fragrances accordingly. The second stage of the eScent wearable technology development will miniaturise this technology even further, allowing it to be embedded into the materials that surround us, opening up a vast range of new markets and applications including for example the military (intelligent insect repellent systems), the motor industry, home furnishings and clothing. The eScent builds on from the *“SmartSecondSkin”* textile project at Central Saint Martins College of Art & Design, which described a multi-sensory approach to biomedical designs, recognizing that all senses interact. It was designed to illustrate a responsive fabric that mimicked the neurobiological delivery mechanisms found under skin [27]. The study investigated the extent to which a built-in MEMS device embedded in a ‘*living tissue*’ could deliver fragrances inspired by the J.G.Ballard quote: ‘*Fashion is the recognition that nature has supplied us with one skin too few, that a fully sentient being should wear its nervous system externally’* [28]. A dress was designed to illustrate a responsive fabric that formed an addition layer of skin, to control the emotional state of the user, via the controlled release of active ingredients for improving Quality of Life. As a conceptual piece, the dress interacts with human emotions whereby the aroma dimension is an integral part of the user’s sensory experience.

Figure 10 “SmartSecondSkin” dress; A living tissue photo by Guy Hills.

7. Discussion and Future Challenges

This paper outlines and updates in a systematic way both the development and convergence of materials (bio & chemo) for use with textile constructs and the expansion in the use of textiles based on microfluidic, nanoscience and bio material discovery linked to new active & conductive) polymers. The range of active materials becoming available is such, that the combination of lightweight, transparent, conformable materials properties, combined with textiles (through fibre creation and fabric constructions) and printable (plastic) electronics and miniaturisation (MEMS & micro fluidics) will revolutionise the future of textile platforms. This will come about through the increasing use of sensors, detectors and delivery systems technologies for healthcare and lifestyle needs and through the use of Ambient Life platforms which support a better life through information, assistive technologies and provision of early choice for human decision making. In many instances, this will be made ever more convenient due to the ubiquitous use of textiles as a familiar and trustworthy mechanism for delivery, beneficial and desirable human needs, wants and wishes.

We outline how this combination of creative design elements and innovative materials serve to provide completely new possibilities through

1. Applied medical futures ('smart' bandages)
2. Terawatt challenge (large organic PV)
3. Personal care & lifestyle choice (wearable aesthetic technology)

The combination of electro, photo and bio active materials integrated into textiles and new wovens will ultimately provide the basis for a new range of ambient assisted living choices. New materials discoveries will yield intelligent materials and interactive surfaces which will in turn allow designers and technologists to exploit textiles (theranostic, assistive healthcare), (solar textiles, 'soft' have renewable energy concepts and wearable technology(printable MEMS/MF in aesthetically attractive constructs) moving far beyond the i-pod/MPS player fixtures and connectors attached to clothing in a rather simple fashion. The next decade will also see the enhancement of all of the above possibilities through further convergence of nanoscalar and nanostructured inorganic and bio materials aligned to textiles, fabrics and large area non woven thin films.

7.1 Converging Nano-Bio-Info Technologies

Pathway biology refers to the integration & synthesis of techniques and approaches which are focussed on obtaining a deeper understanding of inter and intra cellular (molecular) interactions. This can be in the form of 'in silicico'(pls check if silico) methods for presenting and modelling pathways, which can essentially provide the opportunity to predict host-pathogen protein interactions and to carry out pathway therapeutic analysis. Applications are envisaged in the field of theranostics and personalised healthcare, as well as in the development of bio-intelligent medication.

Present and future societal needs, wants and wishes call for improved healthcare offered with reduced risks for the patient and lower costs. These can essentially be met with the provision of predictive preventative and personalised medicine as well as better management of elderly and disabled people. Nanotechnologies can also play an important role in this respect, due to their inherent advantages. Firstly they operate at sizes compatible with bio entities (cells & molecules) and can thus promise better accuracy. In addition, small sample quantities will be required, making procedures less invasive and permitting early diagnoses with bio-sensors.

7.2 R&D Opportunities & Challenges

Wearable systems: seamless technology i.e. garments and devices need to be comfortable and behave like a 'second skin'. The future of acceptable wearable systems is very much linked with 'SFIT' materials. There may also be a need for more advanced materials applications e.g. ubiquitous devices which will become part of textile, flexible fabric substrate materials. An attractive way forward for intelligent textiles is to embed the electronic functionality directly in textiles as shown previously in Figure 8.i.e. combine the mechanical properties of a polymer and the electronic properties of a semiconductor, creating an active, smarter intelligent substrate.

The biggest obstacles in realising intelligent textiles are currently the packaging (encapsulation) and industrial implementation (reproducible, reliable production processes) for active substrates or garments. Cost effective manufacturing and core of manufacturing are thus major issues. Active bio-medical clothes or sensory responsive jewellery can become completely wireless by incorporating a body area network ('BAN') of 'soft' printable sensors/detectors which would facilitate and access wireless data transmission. Transdermal body sensors for non-invasive analytic measurement, analysis and active ingredient delivery are a provisioning area for RandD [29].

7.2.1 Innovative Design Integration with Evolutionary Materials to Create Revolutionary Products and Services

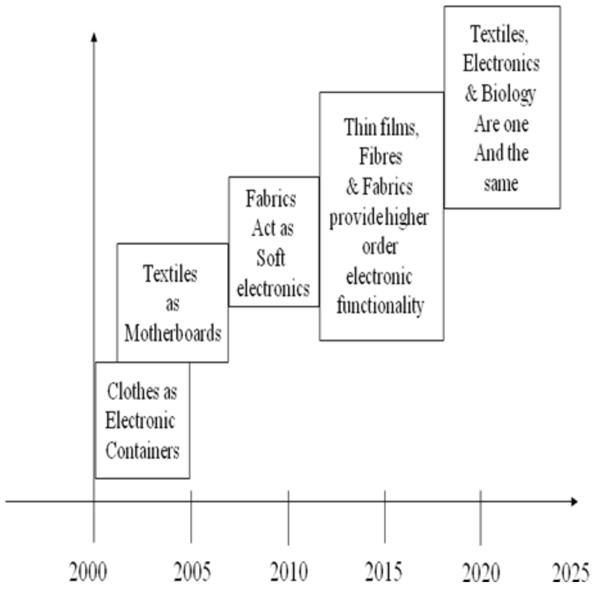

Figure 11 Smart textiles path.

The material 'families', exhibiting compatible, responsive, adaptive and electro/photo-active characteristics, will serve to provide the functional pathway for innovative and imaginative product and service design. The main societal and consumer led needs are:

- Assistive Healthcare applications
- Renewable Energy applications
- Innovative Textiles applications
- i-Mats for Transport and the Built Environment
- Embedded ICT through Printable Intelligence
- Fashion and Lifestyle experiences
- Experimentation and exploration of convenience, ambient intelligence and ambient life
- Experiences created thorough Design

7.3 Sustainable 'Smarter' Textile Constructs

The future of sustainable materials – learning from nature and applying innovative design principles based on interdisciplinary competencies at RCA. What is the central theme setting both options and criteria for design by nature (and by synthetic means)?

7.3.1.

In terms of biological systems, information is distinctly ahead of energetics in any conceptual framework. In turn, information is directly linked to organisation.

7.3.2

In materials processing, nature replaces the massive use of energy, e.g. high temperatures and pressure or harsh chemical reaction environment, with the utilisation of information which equates with structure at all levels, from the molecular scale to macroscopic ecosystems. Indeed, most of the exceptional functionality of bio (and other active) materials is structure composition and morphology based. It is here that the most important aspect of biomimetics emerges, and it has the power to redesign engineering. It also has parallels with the techniques employed within textile, product and architectural design [30].

8. Conclusions

- The 21st century will be the century of materials - we will by 2100, understand how to control both the nano and molecular manufacture of materials by design. This will lead to even greater integration and use of increasingly invisible material systems and devices.
- Functional electroactive materials and interactive textiles will play an increasingly significant role both societally and commercially as more active, responsive and adaptive systems become available for healthcare, energy, security, safety, clothes, entertainment and interactive consumer products and packaging.
- The role of intelligent textile constructs will change, but the importance of textiles as a means of visual communication and creativity will remain. They will always represent a unique record of human behaviour from protection to attraction.
- This paper points the way ahead for some of these evolutionary developments.

Note: The views stated are those of the authors and are not necessarily those of Arrow Science Consulting, Central St. Martins College of Art and Design, or The Royal College of Art.

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