Augmented materials: spatially embodied sensor networks

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Wireless sensor networks (WSNs) are increasingly common in medical and environmental applications. Most WSNs operate in air or liquid media: in this paper we are concerned with the design and implementation of sensor networks embedded into solid materials, thus placing sensing and processing capabilities into the fabric of built objects and environments. We introduce the concept of an “augmented material” and describe an early prototype using off-the-shelf components to capture and interpret interactions. We analyse the future developments required in various component technologies to bring the concept properly to reality.

Categories and Subject Descriptors: D.2.7 [**Pervasive Computing**]: Spatial Computing

Additional Key Words and Phrases: Augmented materials, adaptive systems, near-field communications, packaging

1. INTRODUCTION

Unlike the typical applications of computational devices, the physical environment is at the focus of attention for spatial computing and sensor networks. Computation is used to exert control over physical processes on the basis of environmental or spatial awareness, with the computation being integrated with the control and communication and embedded into a physical system. These embedded systems are generally not designed around human interaction but are rather required to

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work without it in direct contact with the physical world. Their impact on everyday life is growing rapidly: wireless sensor networks (WSNs) are increasingly common in medical, environmental monitoring, intelligent buildings, and other applications. Computation is surrounding us in our daily lives, helping to realise the vision of "ambient intelligence" where technologies are unobtrusive and be taken for granted: Marc Weiser called these *disappearing* technologies [Weiser 1991; 1993]. By integrating computation, communication and control in the physical environment, the well-known interaction paradigms of person-to-person, person-to-machine and machine-to-machine can be supplemented by a notion of "person-to-physical world" [Srivastava et al. 2001]: the interaction with the physical world becomes more important than simple symbolic data manipulation [Cerpa et al. 2001].

One of the key challenges in developing the effective and scalable technologies necessary to realise ambient intelligence is implementing a methodology that genuinely integrates the fabrication of "smart" co-operating physical objects with their creation on a digital level, beyond simply the improvements in miniaturisation deriving from Moore's Law. A "smart table" consists of both a physical realisation and the affordances and behaviours associated with "table-ness": the latter contextualise and interpret the data collected through the former, and facilitate a far more effective and responsive interpretation of the environment than is possible from sensing alone.

Whilst one may envision such systems built *ab initio* from physical materials and embedded sensors, we propose a rather more integrated view: *that we create general-purpose physical materials with general-purpose embedded computing, sensing and communications infrastructure, which can be used to fabricate a range of real-world objects and can be imbued with whatever behaviours their designers require*. That is, we propose moving from a special-purpose, per-application technology to a suite of general-purpose, re-usable and re-purposable technologies integrating wireless sensing and pervasive computing – a similar evolution to that which happened in traditional computing. We term these platforms *augmented materials* [Dobson et al. 2005; Delaney and Dobson 2008], denoting a family of materials with general physical and computational properties.

Fundamental to the notion of augmented materials is the spatially-embodied sensor module, which gathers data from the environment and communicates with other modules to provide a global view of the material's situation. Augmented materials involve embedding micro- and nano-sensing, processing and communications elements into appropriate physical substrates. The substrate provides physical features for objects constructed from the material, sensing support for capturing energy transitions, and a physical embodiment of the network in the real world.

The effective encapsulation of sensing into materials is far from trivial. Each man-made object has intended physical properties. Embedding electronics post-fabrication might cause significant degradation of the original material. A more attractive approach is to embed electronics layers into a material as it is fabricated, allowing unwanted effects to be minimised. Objects fabricated from such materials will acquire sensing, processing and communicating abilities "naturally" – at a cost of requiring electronics that can survive the fabrication, forming and curing processes of the materials into which they are embedded.

In this paper we bring together the concept of an augmented material with a motivating proof of concept and a detailed consideration of the electronic, communication and programing challenges needed to fully realise the vision. Our contributions are (firstly) to elaborate a conceptual architecture for sensor/actuator system physically embedded into general-purpose materials; (secondly) to demonstrate this concept with a rough prototype built from off-the-shelf materials and technologies, from which we fabricate an object able to sense and interpret its environment; and (thirdly) to discuss in details the technologies and techniques being used to realise a more complete and realistic prototype augmented material.

Section 2 presents the concept of an augmented material. Section 3 discusses existing technologies that influence augmented materials, some of which are used in section 4 in prototyping a material and using it to fabricate a simple object. Section 5 discusses component technologies needed to improve this prototype into a realistic material, while section 6 concludes with some future directions for this research programme.

2. THE VISION OF AUGMENTED MATERIALS

Imagine a person with a broken leg who is wearing a walking cast. For a physiotherapist the challenge is to make the person take adequate exercise in order to stimulate the break, while at the same time stopping them from attempting too much and risking further damage. Since the physiotherapy programme changes over time and in conjunction with on-going assessment of the injury, the exercise required of the patient, and the optimal levels of rigidity and support required of the cast, will also change.

Any single material will be sub-optimal at *some* point in the cast's lifecycle: either providing too little support for optimal recovery, or too much for the patient's improving condition. Moreover the patient's own behaviour may be too aggressive or too passive at any given stage – a problem for injured sportsmen and injured children alike – and they may have no indication or guidance as to whether they should exercise more or less. One would therefore like a cast that is sensitive to the evolving physiotherapy programme, and to the patient's pursuit of that programme.

Consider constructing such a cast from an augmented material, with embedded sensing and processing. The cast can sense the load being placed upon it as the person walks around, compare it with a downloaded therapy programme, and react – by for example glowing green when things are fine but flashing red lights if the patient is overdoing their exercise. One could even imagine a material with variable stiffness that could be even more responsive. The programming task is to turn low-level sensor data into high-level behaviour based on the semantics of the object that has been constructed from the material.

The hypothesis of augmented materials is therefore that *physically embedded networks of distributed sensors and actuators can be systemically programmed to augment the behaviour of synthetic materials.* Moreover we contend that the implementation of typical material processing techniques can provide a natural programming construct (or language) for the creation and assembly of functionally effective smart objects from these materials. The notion is that the materials are infused with systems capability that allows a digital representation to be developed at a selected

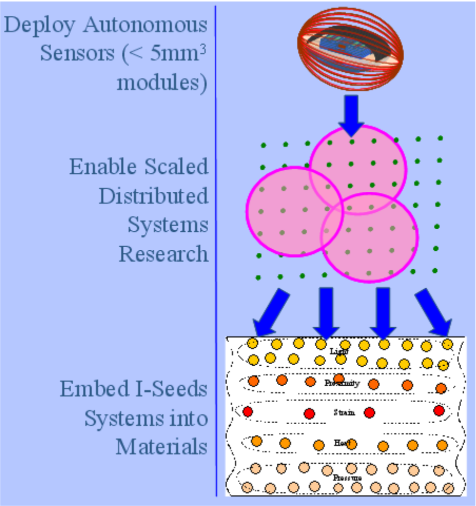
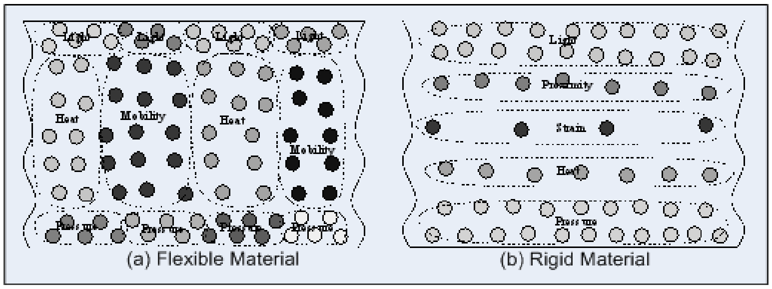


Fig. 1. From nodes to materials

formation stage (*e.g.* curing) and maintained thereafter, and able to sense and report on the environment of the material. Each physical stage of the material's fabrication and processing can be coupled with a digital stage that contextualises the sensor data collected; conversely, sensor information can be used to drive behaviour informed by both low-level sensing and high-level semantics about objects, their behaviours and relationships.

The notion of creating an augmented material is similar to mixing additional component elements into an established material composite in order to affect a particular physical attribute – for example adding nanoscale elements in order to increase tensile strength. In augmented materials, the sensor nodes will be deployed into the synthetic material through a typical mixing process, designed to distribute them randomly but uniformly within the material. Once the nodes are uniformly distributed a process of self-organisation can take place to create a network of nodes, and functional definition of the nodes based upon relative location in the material and the most appropriate physical parameters for these nodes to monitor. In the case of materials where the formation process includes a liquid or viscous fluid stage, the nodes might be designed to have limited 3-D motion. This would allow the physical self-organisation of the nodes from the uniformly random to 3-D forms that would match the node capacity and distribution to all requirements to effectively measure the physical parameters of the material. Figure 1 presents a conceptual outline of fabricating augmented materials.

The resulting network is likely to be heterogeneous, with nodes specialising in sensing, data collection, communications and so forth, and collected into groups of functioning nodes that then federate across the material. The important point is that nodes are sufficiently distributed and sufficiently plentiful to support the intended uses of the material at later stages. The network is by definition strongly correlated to the physical behaviour of the material itself. One could expect that nodes' locations, their function and the structure of the local network groups might



(a) Flexible Material

(b) Rigid Material

Fig. 2. Local network groups depend upon the material in which they are embedded

vary significantly depending upon parameters such as the rigidity of the material (see figure 2). This requires system specifications such as the resolution of the sensory devices to also vary according to these parameters, with a resultant impact upon the computational, power and memory requirements of the nodes themselves. The nature of the material would also impact upon the nodes physical size and its design. Augmented materials are therefore very explicitly co-designed, with variable computational, structural and topological structures.

At the network level, the material should be able to integrate local observations into a global view of its own state. An example might be when a sheet of material is cut, which would manifest itself as a very structured partitioning of the network: a material that “knows” it is a sheet and “knows” about this forming step can interpret this data and react accordingly (for example by modifying its view of its own size and shape).

Similarly a material placed in contact with another can make inferences about this proximity. The structure and data management actions of the embedded network should adapt to the process of combining materials to create objects. In this case, a networking action analogous to that of physically bonding two materials together should take place (figure 3). This “digital bonding” should link the two material networks together and extend the local network groupings across the material boundaries to accommodate nodes with common or similar tasks, and possibly alter the network structure based upon any relevant constraints introduced by physical bonding.

Overall development of the augmented materials network is based upon defined local and global systems architectures (figure 4). The local systems architecture is represented by small sets of nodes designed to measure physical parameters at specific locations in the material. The systems description is determined by the development of two element categories – “sensing” elements and “aggregating” elements – which are evenly distributed through the substrate. The global systems architecture brings together and represents this local data at a material level.

Fully realising augmented materials, where the physical and digital are closely integrated, represents a significant and long-term challenge in itself. However, the framework for implementing augmented materials can be investigated using current technology platforms and programming approaches. More importantly, the methodology should become a guide for effective implementation of augmented materials as a practical, physically integrated, heterogeneous architecture.

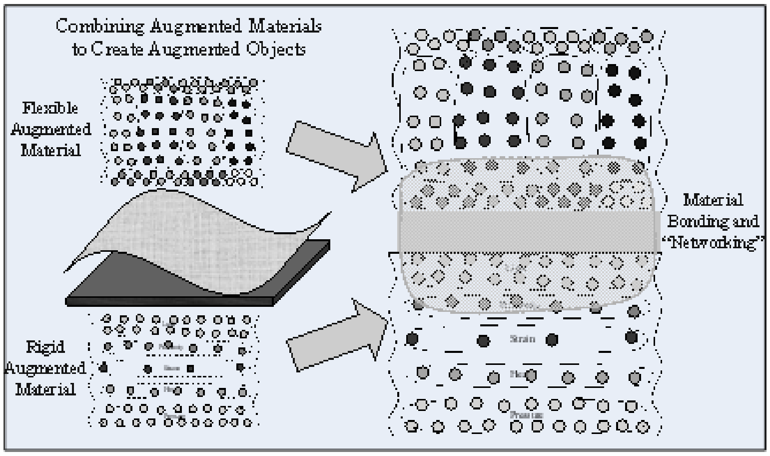


Fig. 3. Forming objects through “digital bonding”

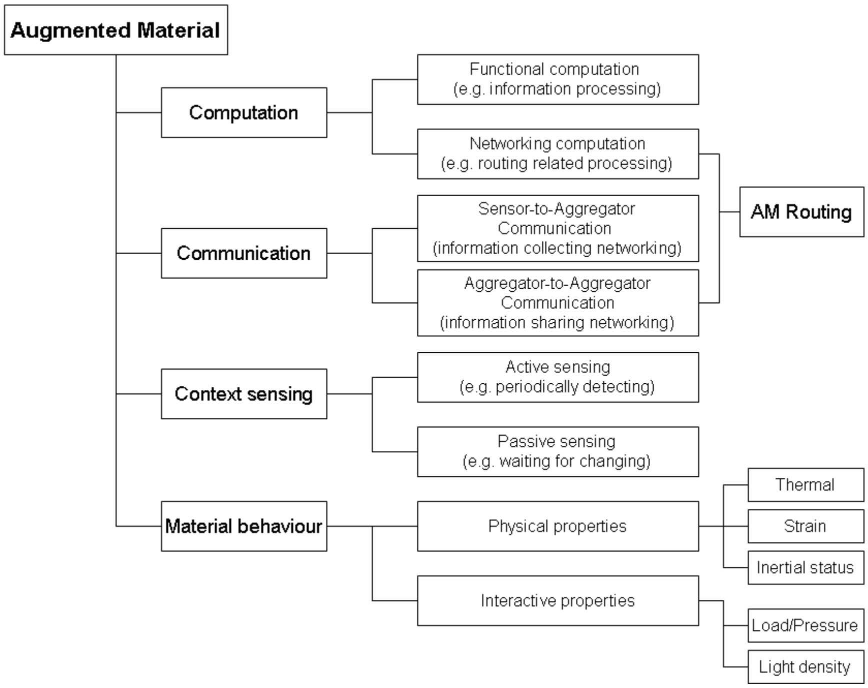


Fig. 4. Functional block diagram of an augmented material

3. RELATED WORK

3.1 Smart materials

A number of research domains are associated with increasing the functional capabilities of material systems. In the domain of materials research, the influence of biological systems is having an impact: a particular example is that of self-repairing polymeric composites [Giurgiutiu et al. 1996]. In this case, a healing capability is imparted through the incorporation of material phases that undergo self-generation in response to damage. A related research activity is that of self-regulating materials [White et al. 2001] that can be created by using magnetostrictive particles as "tags" in a host composite material: their interrogation and response indicates the position of damage. These techniques are obviously relevant to augmented materials and reveal a form of autonomic behaviour that would have clear value when integrated into larger intelligent systems. They are however "dumb" materials, in the sense that their responses are pre-determined and cannot reason about the effects they undergo or be linked to a wider infrastructure.

The concept of immersing the computer more fully into the fabric of daily life is vital to achieving a genuine representation of ambient intelligence, and a wide literature now exists concerning the design, construction and evaluation of pervasive systems. The FiCom project [Healy et al. 2004] investigates new forms of silicon substrates to provide platforms that may be more effectively integrated into many kinds of object. Research in this area has uncovered intriguing possibilities for using silicon in application domains, such as the development of smart bandages. Perhaps more effective is the increased use of the thin silicon, specifically for smart card technologies and high-density 3-D integration [Chen et al. 2000; Kelly et al. 2000; Al-Sarawia et al. 2002].

An inherent part of the development of augmented materials is spatially distributed, embedded sensing and, ultimately, actuation. An investigation on compliant systems [Trease 2007] has provided a mathematical framework for distributed actuation and sensing within a compliant active structure. The method, which synthesizes optimal structural topology and placement of actuators and sensors, was applied to a shape-morphing aircraft wing demonstration with three controlled output nodes. Other investigations, focused with the domain of electronic packaging, investigate the sensor devices required to monitor material behaviour [Barrett et al. 1995]. They also highlight the negative impact of embedding electronics in polymeric materials [Egan et al. 1999] and the necessity for care in the design of both the sensor/aggregator element substrates and in the integration process itself.

3.2 Computation and networking

WSN architectures can be characterised by the amount of processing that takes place on sensed data within the network, before that data is reported back to a base station. In-network processing typically reduces external communications and makes for simpler interfacing, at the cost of more extensive embedded processing power. Modern networking stress self-management, self-healing in the face of damage and so forth: the so-called *self-* properties* from autonomic computing and communications [Dobson et al. 2006].

The controller or microcontroller used in nodes sets the WSN's processing power.

Microcontrollers are used in several wireless sensor node prototypes include the Atmel processor or Texas Instrument's MSP 430. The Atmel ATmega 128L is an 8-bit microcontroller intended for embedded applications and equipped with relevant external interfaces for common peripherals. Texas Instrument provides an entire family of microcontrollers under the family designation MSP430 explicitly intended for embedded applications. These run a 16-bit RISC core at low (by modern standards) clock frequencies (up to 4 MHz), but come with a wide range of interconnection possibilities and an instruction set amenable to easy handling of peripherals of different kinds. The family features a varying amount of on-chip RAM (2–10kb), several 12-bit analogue-to-digital converters, and a real-time clock. It is certainly powerful enough to handle the typical computational tasks of a typical wireless sensor node. Research are still ongoing miniaturisation of this controller in micro-scale even nano-scale range.

The emergence of cost-effective tag production technologies [Want 2006; Roussos 2006] has opened exploitation routes for pervasive concepts, for example tag readers embedded in shelves progressing to a "smart shelf", expressed as an "internet of things" [Gershenfeld et al. 2004]. Inductive-coupling-based near-field communication (NFC) [Chevalerias et al. 2005; Välkkynen et al. 2003] can be used within sensor networks to enhance overall lifetime. Toolkit approaches [Hill and Culler 2002; Polastre et al. 2005] developed as part of projects such as Smart-ITs [Healy et al. 2004] and Extrovert Gadgets [Gellersen et al. 2002], are useful in studying the architectural requirements for the effective, autonomous operation of distributed embedded systems. Autonomous sensor platforms (for example [Barton et al. 2005; Brady et al. 2001; Sen]) are suited to providing a foundation for investigative studies on the architectures of the distributed, embedded elements. The ability to enable the control of certain aspects of the behaviour of autonomous systems is particularly important. Emerging subsystems, such as modular robots [Askins and Book 2003; Zhang et al. 2003] , self-sensing sensors and actuators [Hanson and Levesley 2004; Shang et al. 2006] and reconfigurable wireless sensor nodes [Holmquist et al. 2001] are equally relevant and can be integrated with the toolkits to develop the simplest feasible sensing and computational elements.

3.3 Smart objects

Research works on smart floors, smart matter and digital clay are providing insights that can usefully be incorporated into the design of unobtrusive and intuitive interaction within the augmented materials. In this context, "objects" of particular importance in our everyday environment have become the focus of augmentation research. One of many possible examples is the smart floor. An avenue of recent research in this domain has yielded the "magic carpet" [Paradiso et al. 1997] comprised of a grid of rugged piezoelectric wires hidden under a carpet coupled with Doppler radars to measure the upper body motion of users and the "Litefoot" system [Fernström and Griffith 1998]. The "smart floor" [Orr et al. 2000] used load cells, steel plates, and data acquisition hardware to gather ground reaction force profiles and non-invasively identify users to an accuracy of over 90%. A pressure-sensitive floor system [Srinivasan et al. 2005] has been developed with a sensor density of one sensor per square centimetre to support multimodal, high resolution sensing; the design integrated closely with video, audio and motion-based sensing technologies. This illustrates the benefits of creating systems that support interoperability.

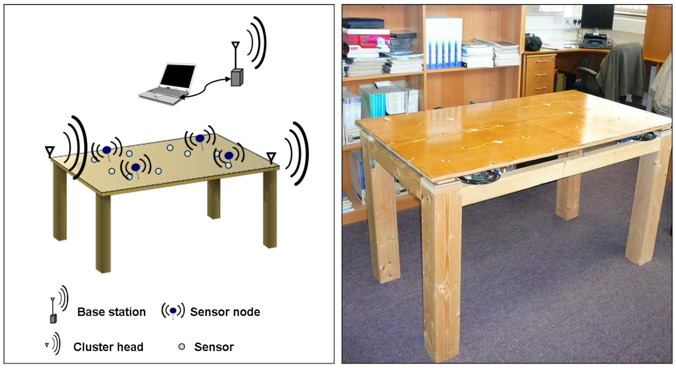
In reality, individual objects typically provide only narrowly-defined services and affordances. Therefore objects should broaden their capabilities through co-operation. This generates requirements upon systems within the Internet of Things, that they support strong, semantically rich, spontaneous and sporadic composition to maximise their behavioural flexibility. This in turn seems to require the availability of reasonable computing power, communications capabilities and semantic technologies.

Networking and distributed computation can also be built into individual objects to address aspects of their performance. The Z-tiles project [Richardson et al. 2004] developed another form of smart floor by building a self organising network of nodes, each connected together to form a modular and flexible, pixilated, pressure-sensing surface. This project is particularly interesting in relation to the concept of augmented materials because it utilizes a distributed networking approach that offers performance and scalability. In particular, as individual Z-tiles provide build blocks for both the physical floor space and for the underlying sensor and computational network. Another example is dynamically reconfigurable artificial sensate skin consisting of modules developed in S.N.A.K.E project [Perez 2006].

Programmable Matter, Claytronics and Paintable Computing related works help in making the augmented materials programmable. Amorphous computing [Abelson et al. 2000] investigates system-architectural, algorithmic, and technological foundations for exploiting programmable materials whose "atoms" are based on a miniaturised (millimetre-scale) integrated circuit with an onboard microprocessor, program memory and a wireless transceiver. Claytronics [Goldstein et al. 2005] explores methods to reproduce moving physical objects based upon the idea of dynamic physical rendering, where programmable matter is used to mimic a physical artifact's original shape, movement, visual appearance, sound and tactile qualities. A related concept is paintable computing, which is described as "an agglomerate of numerous, finely dispersed, ultra-miniaturised computing particles; each positioned randomly, running asynchronously and communicating locally" [Butera 2002]. The physical test-bed developed as part of the paintable computing investigation is also of interest: the Pushpin computing wireless sensor network platform [Lifton et al. 2005]. A similar approach was adopted within the Pin and Play project [Laerhoven et al. 2002]. Both of these concepts provide insight into enabling methodologies for networking in augmented materials at a prototype level: the challenge in this context is to evolve the approach from 2-D surfaces to 3-D embedded elements.

3.4 Assessment

This brief roster of technologies indicates that there is a considerable literature and technological base upon which to build the notion of an augmented material. However, the novelty of the augmented material approach is in its treating of sensing and computation as *another capability* within the materials that can be used to fabricate a particular object. This requires that a range of technologies be integrated into a system that functions *both* as a computing platform *and* as a material capable of the required physical tasks.



(a) (b)

Fig. 5. (a) Schematic of sensing system (b) Image of the table

4. DEMONSTRATING THE CONCEPT

Two initial questions to be answered are: is it possible to build a material that can sense its environment? and, can that material be formed into an object that can leverage self-description in interpreting that data? We have attempted to answer these questions using a simple proof-of-concept demonstrator built using simple materials and off-the-shelf, non-embedded components.

Whilst it is clearly the case that one may build a “sensor table” using existing technologies – and indeed such objects have been built several times – our goal in this experiment is slightly different. Rather than investigate *particular* applications, we want to explore (firstly) whether a material can be used as a general platform for sensing general energy transitions affecting it, and (secondly) whether this material could be made sufficiently generic to address several different application domains. Furthermore we aim to address these questions without extensive technological development.

We use a table structure shown in figure 5 as an experimental testbed. The table top is made of medium-density fibreboard and is 139cm long, 79cm wide and 1.9cm thick. It is equipped with a number of various sensors: strain gauges, thermistors, light sensors, tilt switches and load cells. These sensors constitute the sensory component of the table’s intelligence (awareness of its own state), whereas additional electronic components and subsystems deployed onto the table, such as sensor nodes and cluster heads comprising conditioning circuits and RF modules, represent the communicating and processing capabilities of the table. The intelligent system integrated in the material of the table allows for the table to be dismantled and assembled again while maintaining its intelligence. This capability essentially constitutes the material of the table an augmented material. The following subsections discuss separately the hardware and networking aspects of the system and present experimental results.

4.1 Sensors and supporting hardware

The main elements of the intelligent system integrated in the table are the sensors, sensor nodes and cluster heads. A laptop PC is used as a remote base station.

Fig. 6. Schematic of sensor deployment

Component/subsystem	Units	Elements	Function
Strain gauges	60*		Sensing
Temperature sensor	4		Sensing
Light sensors	4		Sensing
Load cells	4		Sensing
Tilt sensors	4		Sensing
Sensor nodes	14**	RF module (XBee); conditioning circuits	Direct access to sensors, sensor output aggregation and transmitting to cluster head
Cluster heads	4	RF module (XBee and Tyndall 25mm)	Aggregating sensory information received from sensor nodes; transmitting information to base station through best route and routing packets from the other cluster heads
Base station	1	Laptop PC	Data aggregation, processing and analysis

* Organised as 30 orthogonal pairs
** Organised into 4 clusters

Fig. 7. The demonstrator system

Figure 6 schematically illustrates the full sensor deployment layout on the testbed. Specific details and functionality of the components and associated hardware subsystems are described in figure 7.

While for the majority of the sensors the actual location within the table is somewhat optional, deployment scheme for the strain gauges is important for the strain resolution and accurate representation of deformation state of the table top. To address this, an investigation into the optimal strain gauge deployment scheme (number of sensors and their spread across the table) was undertaken [Liang et al. 2009]. The strain gauges were deployed according to the optimal layout shown in

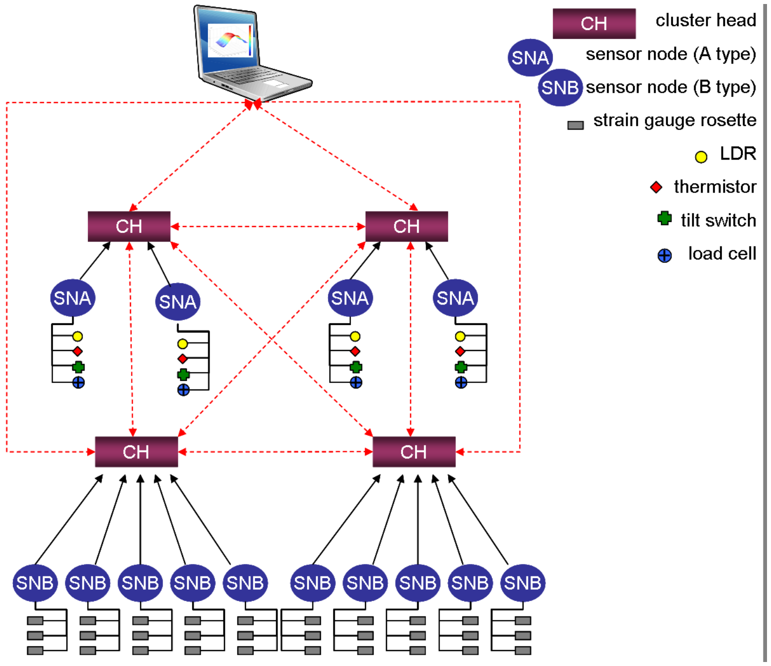


Fig. 8. Schematic of the network

figure 6. Two orthogonal sensors are present at each location to measure strain in longitudinal and lateral directions. In order to eliminate any possible thermal effects on the strain gauges, each gauge is mirrored by a second one attached at the bottom of the table top. Each such pair is arranged in Wheatstone bridge where one strain sensor is measuring compression and the other is measuring decompression. Other types of sensors are assembled at the corners of the table surface.

An efficient methodology for collecting the sensory information in real-time is required when building a sensing object. In this work, a multi-tier architecture is adopted for transmitting local sensing information to the base station where the data is aggregated, processed and analysed (figure 8). The network of this system is structurally separated into two tiers: a set of local sensing networks and a routing network. The purpose of organizing the networking in this way is to avoid the dependency of the wireless sensing ability on the networking in the system architecture. The advantages of such approach are: (1) more scalable, sensing networks are embedded in sections of the object of interest as opposed to one network covering the whole object; and (2) more robust, sensing networks are organized through cluster heads but work independently so that one sensing network is not be affected by failures of others. A cluster head is responsible for both communicating within the cluster and routing information across a mesh WSN to the base station. Scalability of the system means that electronic capabilities can be maintained when the substrates of local networks change their spatial position or the object changes its shape. These changes represent dynamic behavior of the whole sensed target.

4.2 Sensing network

According to the sensor deployment introduced before, strain information from 30 specific positions and information on light, temperature and force load from 4 corners on the target needs to be collected. At each position, there is a rosette comprising 2 strain gauges. The challenge here is to manage the collection of strain information independently generated on each strain gauge. Commercial WSN RF XBee module was selected as sensing node. It supports IEEE802.15.4 protocol stack and has integrated 6 Analogue to Digital Converter (ADC) channels, and a microcontroller. Using the module, one can access 6 strain gauges using those ADC channels. Thereafter, 10 modules are required to service all 60 strain gauges. Since 6 strain gauges can be located at 3 positions close to each other, 30 positions can be split into 10 independent sensing sections: SNB1 (sensor node of type B number 1) to SNB10 (figure 8) covering the whole table physically. Similarly, sensor nodes SNA1 (sensor node of type A number 1) to SNA4 are assigned to collect multi-type sensing information on the corners of the testbed. All assigned RF modules work completely independently and only communicate asynchronously to the cluster heads without any interference from each other. Following this approach, strain information about the entire table surface is collected discretely so that failures of modules in some sections will not affect the rest of running modules. Sensing capabilities can be still available, when table surface is physically dissembled into parts, as long as RF modules and sensors retain their integrity.

4.3 Routing network

All 14 RF modules need to be organized to provide efficient disseminating locally collected sensory information to the base station for analysis. Conventional direct connecting all modules to one single base station (a star topology) would introduce large transmission contention and would negatively affect network scalability and robustness. We solve this problem through implementing one routing network on top of local networks. This routing network is intended for packet routing. Therefore, 10 SNB type nodes are divided into two clusters for simplicity and efficiency of the routing network. Besides these two clusters dedicated to collect strain information, there are two more clusters assigned to collect other context information of the testbed (temperature, load, motion and light).

4.4 Experiments and Results

Two scenarios of experiments were implemented for demonstrating functionalities of this sensing system from different perspectives.

Scenario A: Strain distribution analysis A single weight of 5.6kg was placed at four different positions at the table top. Evolution of strain distribution in the table top with the change in load location is plotted in Figure 9. For this, readings from 30 sensor locations were converted into strain and a strain map was built using surface interpolating function in MATLAB. Analysis of resultant strain maps (figure 9) concludes that they are consistent with their respective loading conditions.

Scenario B: Multi-sensing analysis This experiment lasted four hours. A weight of 5.6kg was placed in different locations on the table top whereas a heater is turned on for the last two hours. Figures 10 presents load information detected

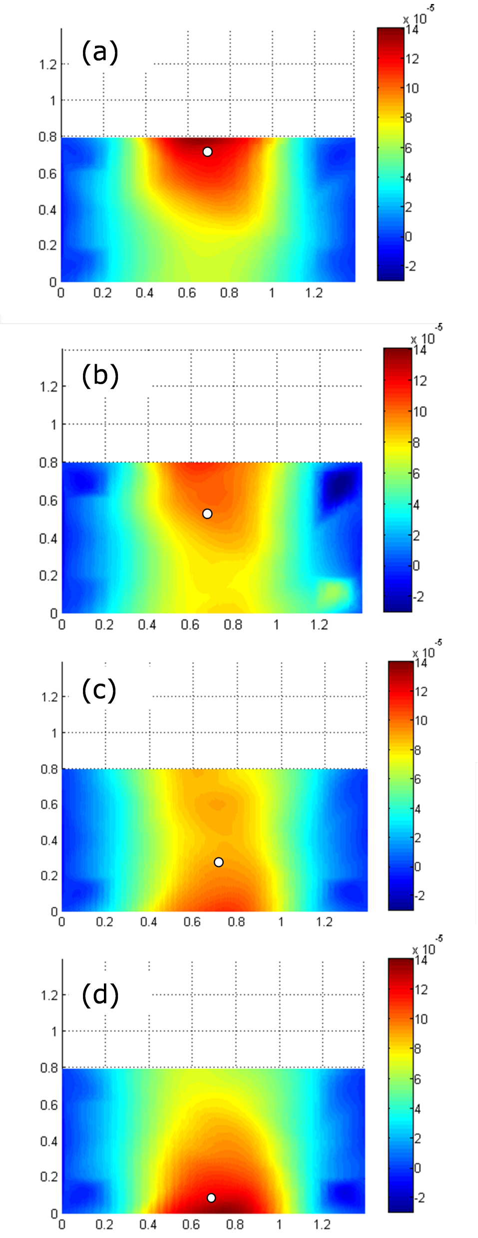


Fig. 9. Evolution of measured longitudinal strain in the table top due to mass load of 5.6kg applied at various locations (marked with white circles)

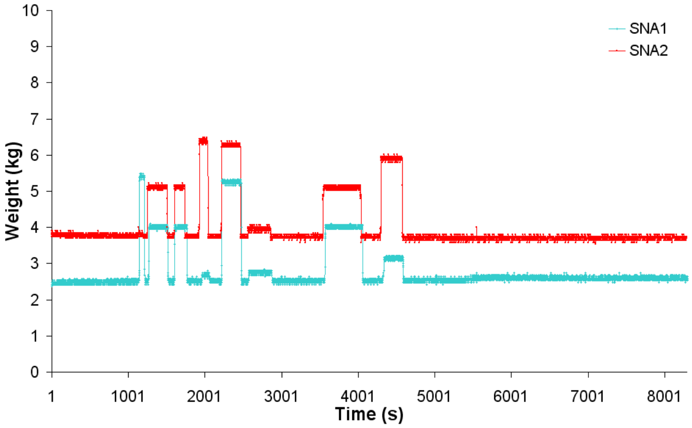


Fig. 10. Time dependent plot of load output from sensor nodes SNA1 and SNA2

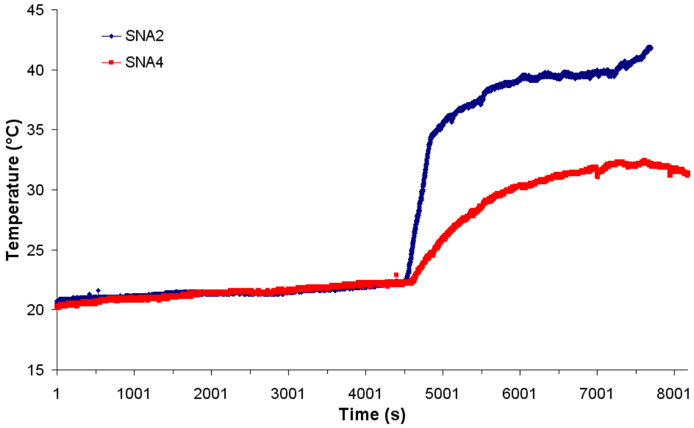


Fig. 11. Temperature evolution reading from nodes SNA2 and SNA4

on left side of the testbed. Figure 11 illustrates temperature data collected from two sides of the testbed, one of which is closer to the heater than the other.

4.5 Assessment

The above experiment demonstrates that it is possible to sense a wide range of energy transitions affecting a material, and to derive interpretations of this sensor data according to a higher-level understanding of the object the material is formed into.

The specification for the accuracy and resolution of strain measurements and the geometry of the table required that the sensors be organised in a uniform grid-like manner. This being the first prototype, and being made of a material that is hardly easily-workable, also imposed a limitation on our ability to fully embed the electronics in the MDF. In a more generic view of augmented materials and in the next generation of prototypes the sensors will be fully encapsulated in the host material and randomly distributed within its fabric.

The remote base station represented by a laptop PC will in future be integrated into the augmented material. Such computational capability can be contained in one extra cluster head or, more flexibly, be provided collectively by a number of cluster heads integrated in the material: various cluster heads may be empowered with various computational capabilities which together constitute full capacity of the base station. Such an arrangement would allow better resource management and parallelisation of certain processes.

5. A TECHNOLOGY ROADMAP

Given the above confidence in the ability of a material to acquire and interpret sensor data, we now move on to consider the new technologies and approaches that need to be developed in order to move from the initial prototype of section 4 to a more realistic prototype augmented material. In this section we review the requirements for new technologies in communications, programming, fabrication and encapsulation. Our goal is to set out a road map for the research programme to develop a functioning augmented material.

5.1 Communications technologies

Embedded sensors are the heart of the augmented materials. Selection of a proper and power efficient communication technology for these sensors is very important. Considering the placement and management (during the fabrication and post fabrication) of connectivity within the augmented materials we conjecture that wireless communication technologies can provide better and flexible solutions than the wired one.

Near Field Communication (NFC) is a short-range wireless connectivity standard (Ecma-340, ISO/IEC 18092) jointly developed by Philips and Sony, specifies a way for the devices to establish a peer-to-peer network to exchange data. It exploits magnetic field induction to enable communication between devices when they're touched together, or brought within a few centimetres of each other. After the P2P network has been configured, another wireless communication technology, such as Bluetooth or Wi-Fi, can be used for longer range communication or for transferring larger amounts of data.

We expect NFC to provide a potential solution for enhancing existing and emerging mobile applications with data acquisition from various sensors. NFC supports the use of mobile handsets by touch-based interaction, which is an intuitive and user friendly way of establishing connections and exchanging information between mobile handsets and other devices [Välkkynen et al. 2003]. Application of NFC to large scale WSNs is not well explored and this is why one of the key objectives this work is to explore the possibilities of NFC in WSNs with high sensor density.

Generally in augmented materials communication will happen between sensors and processors, between elements (sensor nodes), and between materials. It also requires a communication mechanism to the external world. In augmented or smart material sensor density is expected to be moderately high [Rangarajan et al. 2007] and the inter-element or inter-sensor distance will be in the range of few centimetres, allowing for the use of NFC. Even for inter-material and external communications, we can exploit NFC if the separation between elements and external world is less than 20cm. Even with such a short communication range NFC could be a very effective and efficient wireless communication technology due to its low power requirements and low maintenance.

Lifetime NFC enables longer lifetime of the sensor battery compare to its counterparts, especially Bluetooth. As NFC is capable of transferring power between devices, fundamentally NFC enables semi-passive implementation of sensors with multi-month to multi-year battery lifetime and even passive implementation without any power source. However, this calls for commercial NFC technology that supports zero-power operation of the NFC transceiver (similar to RFID tag) when waiting for activation from an active NFC device, and efficient power management during communication.

Communication setup latency Instead of performing manual configurations to identify Bluetooth devices, the connection between two NFC devices or sensors is established at once (under a tenth of a second). This shorter setup is not only saving time but also saving energy, as radio and other devices will be active for shorter time. Even in power saving mode option will save more energy as it needs less time to setup the communications.

Scalability Due to its shorter range and near field coupling, NFC is more immune to eavesdropping and intentional or unintentional interference. This really helps NFC to scale to large networks.

Sensor density From analysing existing projects, it is clear that the average inter-element or inter-sensor distance considered desirable is less than around 20cm. This strongly suggests that for inter-sensor or inter-elemental communications NFC could be a suitable candidate and inter-elemental communication is one of the key communication aspects for augmented material concept.

Maintainability As both the environment of a WSN and the WSN itself change (depleted batteries, failing nodes, new tasks), the system as a whole has to adapt. As NFC enables longer lifetime of the sensor battery compare to its counterparts it will require considerably lower maintenance in terms of system up-time: this does not of course obviate the need for network re-configuration in response to node failures.

Security With less than 20cm range, NFC provides a degree of security and makes it suitable for crowded areas where correlating a signal with its transmitting physical device (and by extension, its user) might otherwise prove impossible..

Cost Pure NFC communication enables lower price, since NFC is technically less complex than Bluetooth and other technologies.

Compatibility NFC is compatible with existing RFID structures. Moreover, NFC can provide easy to use touch-based access to the sensor data by lowcost mobile phones and other mobile handsets, which make the application specific-reader device unnecessary and thus decrease the system level costs dramatically.

Communication range is the main limitation of NFC compared to Bluetooth but still with this limitation it makes the physical browsing simpler and easier. The maximum data transfer rate of NFC (424 kbit/s) is slower than Bluetooth (2.1 Mbit/s). Even though data rate is low compare to Bluetooth but this will be sufficient for most of the sensor network applications as the average data rate of a single node rarely exceeds 1kbits/s [Otis and Rabaey 2007]. These disadvantages can be partly overcome by combining NFC with Bluetooth or Zigbee, which on the other hand will mean that some of the advantages such as the lower price of pure NFC implementation are lost. Still, this is an important aspect in NFC application possibilities.

If we consider using NFC rather than “standard” wired communications in the table demonstration of section 4, we can see that the technology has the potential to radically simplify systems development. So far in the smart table we used 10 processing modules or sensor boards and if they are evenly placed or embedded over the table surface (139 x 79cm) then it is possible that the distance between the processing module and a strain gauge will be around 12cm (vertically) and 21cm (horizontally). The existing quantity of strain gauges may need be increased to provide improved coverage and then both distances will come down to less than the maximum communication range of NFC (20cm). Equally, if the 60 strain gauges are evenly embedded over the table surface then the inter sensor distance will be around 13cm.

5.2 Programming

The distinguishing feature of spatial computing is that the physical location of elements plays a critical role in the operation of the computing system, the conditioning of its behaviour and the interpretation of any data it collects. This requires a significantly different programming approach than traditional systems, which have typically either ignored or actively masked location.

For most sensor networks, the goal of the network is to return data to a fixed base station or to the wider internet. There may be a certain amount of in-network processing of data to reduce traffic and improve data quality. The programming framework may operate at the level of individual nodes, or may allow groups of nodes (or indeed entire networks) to be programmed *en bloc*. There will almost always be redundancy and robustness built into the communications and other protocols, to handle the (common) occurrence of node failure and network partition. A critical metric for many networks is the amount of node or link failure they can incur before failing.

A sensor network in free air or a liquid medium is an end in itself; an augmented material, however,is used in the construction of objects. In building a table from an augmented material, for example (section 4), the augmented material is used construct the final, sensorised object that is of primary interest to designers. Similarly there may be augmented objects placed upon the augmented table, and it is these objects, and their interactions, that are of most interest when programming applications. Moreover, forming a material into an object adds an extra layer of meaning to the way in which that object should interpret its environment and interactions: it’s “table-ness”.

We may therefore view an augmented material system at four levels. At the *physical* level the substrate exhibits mechanical and other properties that condition its use. At the *element* level, each embedded sensor element will make local observations that can be communicated with its neighbours. At the *material* level, these individual observations may be aggregated to form a global view of the material and its environment. Finally, at the *artefact* level the object can use knowledge of its purpose to interpret the aggregated data.

Programming an augmented material can make use of information at all four levels: physical constraints limit the range of possible observables; individual elements have particular characteristics in terms of capability and accuracy; all the elements within the material must be co-ordinated in a robust and power-efficient manner; and the behaviour of an artefact captures the purpose it serves in the overall environment. The second and third levels are common to all sensor networks; the first occurs because of the use of a substrate to encapsulate the elements; while the fourth allows high-level notions of pervasive computing to be imported directly into the programming challenge.

The importance of location in environmental sensing is often not so much in the literal, absolute sense, but more in terms of the relationship that a node has to particular physical processes. In sensing water-borne pollutants, for example, one may use a model of the underlying phenomenon being sensed (pollutant introduction, fluid flow, diffusion and so forth) to drive the management and placement functions of a sensor network [Dobson et al. 2009]: the physics of the situation defines the most effective sensor constellation that should be used to sense it.

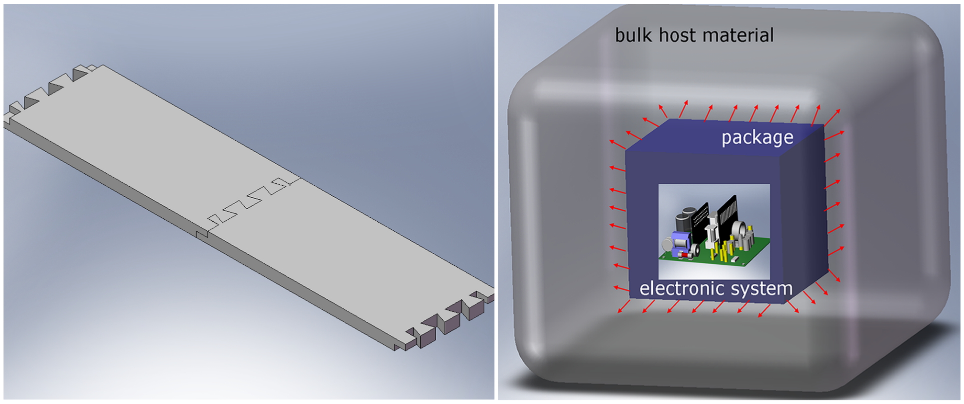
An example of this process might be to aggregate strain measurements across a material and, coupled with information about the material's stiffness, compute the expected shape of the material given the strains it is under – integrating local observations into a global state. The significance of this process is that combines observation with interpretation – low-level sensing with high-level physics.

This combination of levels poses a challenge for a general-purpose platform. At the most abstract level one might perform simulations or numerical solutions of differential equations to interpret the sensor data, but neither approach is feasible with microcontroller-class processing power. More symbolic approaches using machine reasoning, possibly combined with semantic technology such as RDF and OWL, show more promise, although need to be considered carefully in the context of resource constraints.

A more general question is one that recurs throughout pervasive and adaptive computing: what is the most appropriate programming model for expressing the sorts of behaviour the systems should exhibit? Several different paradigms have been explored (as surveyed in [Dobson et al. 2006; Sugihara and Gupta 2008]), and it seems clear that a re-usable, general-purpose model is still lacking. Our feeling is that a programming model that combines reasoning with physical constraints within a well-founded framework – for example using notions from topology to facilitate global computation from local observations over time – may be a promising avenue for exploration.

5.3 Fabrication and encapsulation

With the advances in material science and technologies the choice of materials is wide and is subjected mostly to the needs of the ultimate applications. In case of polymer materials, for example, encapsulation involves placing the packaged intelligent system into a mould, injecting liquid plastic into the mould and curing it. This can also be done in layers, where series of placing electronics and plastic curing steps take place. Integrating intelligence into wooden materials may resemble a laminating process where thin low-profile components are placed between the



(a) (b)

Fig. 12. (a) Schematic of blocks of augmented materials linked together (b) Schematic of the packaged electronic system embedded into bulk material)

layers of laminate and then bonded together. The concept of augmented materials also lends itself to modular smart systems. For this, modular blocks comprising electronic system encapsulated in a polymer block can be joined together using an interlocking system in 1-D, 2-D or 3-D manner to create a large area smart object (figure 12(a)).

One of the challenges with augmented materials is related to the intelligent systems being fully embedded/encapsulated into the bulk material. Incorporating packaged distributed, networkable computing and sensing systems into various materials without compromising the desired performance and reliability specifications of the host materials, and ultimately smart objects, is not trivial. In this scenario, the systems packaging becomes the main interface between the electronics and the host material and subsequently needs to be functional to both, the system inside and the bulk material outside. When embedded into a material, the packaged system perturbs the natural structural morphology in a local continuum thus generating undesirable stresses and becoming a stress concentrator (figure 12(b)). The stresses are induced into the host material during the thermal cycle of encapsulation and during everyday use and result from mismatches in thermal/mechanical properties between the embedded package and the host material. These stresses are highly undesirable as they undermine the material's structural integrity and ultimately the smart object's functionality and reliability. Problems such as delaminating, cracking and fatigue fracture may occur and eventually render the object unusable. The magnitude of the stresses depends upon a combination of several factors, including the package design, the materials used and the encapsulation/operating conditions. Existing standard electronics packaging solutions, the majority in a cubical shape, have not necessarily been developed with the purpose of embedding and as a result are mostly unsuitable for use in large scale embedded systems. In fact, no dedicated technology serving the above purpose exists to date. Therefore, new robust and reliable packaging design solutions and technologies for "seamless" integration of digital systems into materials will be needed to realise smart objects and environments of the future. This will require an entirely different approach to the package design. The work in [Lishchynska and Delaney 2009] provides some insight into the effects of embedded packaged system on host materials. Through experimental studies and employing finite element analysis (FEA), it explores various possibilities of mitigating the issues and suggests package design solutions to minimize the detrimental effects. Development of augmented materials, and the hardware aspect in particular, is reliant on new package design solutions ensuring an unobtrusive presence of the packaged electronics in the host materials.

6. CONCLUSIONS AND FUTURE DIRECTIONS

Ambient Intelligence depicts the convergence of ubiquitous/pervasive computing, ubiquitous communication, and interfaces adapting to the user. In the ambient intelligence vision humans will be surrounded wherever they are by unobtrusive, interconnected intelligent or smart objects. Creating such smart or intelligent objects, and hence smart spaces, is the focus of much research attention. Insufficient attention has been paid to the technologies by which intelligent objects may be created *en masse* and imbued with the necessary intelligence to contextualise and respond to their changing environments.

In this paper we have presented the concept of augmented materials as a reusable, re-purposeable, general-purpose spatial computing platform for the construction of objects with embedded sensing and intelligence. We have surveyed the existing technologies and demonstrated that they can be used to built materials that can be formed – rather inconveniently – into smart objects. We have developed a road map for technologies needed to develop a more functional augmented material, including issues in communications, programming, fabrication and encapsulation.

Our immediate next step is the development of a realistic prototype material. The focus will be on encapsulating miniaturised sensors and sensor nodes into polymer materials (for example a foam) and investigating the effects of embedding the electronic layer in the material on the scalability, reliability and robustness of the whole system. Additional focus needs to be placed on network capability to reorganise itself when physical sections of the material are re-configured (assembled or dis-assembled). Although simple, this will allow us to explore issues in the forming of materials into objects: the interpretation of cuts and bonding, as well as the integration of sensor data alongside the material's known physical properties to demonstrate self-awareness. An example of this would be the foam "knowing its own shape" by integrating observed strains across its volume.

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