# 17
# Sensorial Materials

*Dirk Lehmhus, Stefan Bosse, and Matthias Busse*

## 17.1
## Introduction

By our definition, sensorial materials are materials that are able to feel, that is, materials that can gather and evaluate sensorial information. The definition is wide enough to accommodate different kinds of physical or chemical signals, but it does call for integration of the associated sensor nodes or networks in the material, and for additional data-processing capabilities. Naturally, aspects such as provision for (internal and external) communication as well as a reliable energy supply need to be added [1, 2].

The natural equivalent of such a technical system is the nervous system of the various animal genera. For them, it is the basis of one of the defining characteristics of life itself, irritability or the response to stimuli. The technical motivation to reproduce nature's invention is manifold, as are the envisaged applications. Within the context of this book, we will confine ourselves to advantages foreseen in the field of load-bearing structures, and thus naturally to usage in structural health monitoring (SHM). SHM is well established in civil engineering [3] and currently being discussed for aerospace applications. In the latter field, the transition from metal to composite aircraft structures reflected in several chapters of this work has raised concerns with respect to these materials' typical response to impact loading: Optically non-detectable failure may occur, calling for a constant monitoring of the state of the material. The transition from the metal-dominated ''silver eagle'' to the composite-based ''blackbird'' is therefore expected to provide a major boost for SHM not only in terms of market penetration, but also technologically, as it is likely to fuel developments toward sensor-integrated and sensorial materials [4, 5]. Aerospace structures call for component sizes orders of magnitude smaller than what is acceptable for bridges, the present mainstay of SHM applications.

Safety of potentially impact-loaded composite structures is one motivation for implementing SHM or, to begin with, load-monitoring systems. There are others, too. Knowing the exact state of a structure at any moment in time allows timing of maintenance work according to actual needs. Need-based, as opposed to regular, maintenance can reduce operating costs specifically in industries where high costs are incurred either by the maintenance work itself or by taking the object of maintenance out of service. Offshore wind energy plants and commercial aircraft are examples in this respect. Further advantages may be realized wherever damage-tolerant or fail-safe as opposed to safe-life dimensioning is applied as design philosophy. Here, constant monitoring in conjunction with an understanding of the development of damage over time will enable predictive maintenance strategies as well as weight savings based on an adaptation of safety factors. The latter would be justified by the greater proximity to damage development achieved by means of an integrated system. Current developments in the field of load and SHM systems for fiber-reinforced composites are discussed in Chapter 8 on polymer matrix composites.

Having thus defined sensorial materials, a distinction has to be made with respect to certain types of stimuli-responsive materials sometimes referred to as *self-X materials*. The best known among these and probably the example developed furthest are self-healing materials [6]. In these materials, aspects such as structure, constitution, and composition are predefined in a way that one specific stimulus will result in one specific response of the material. Thus the link between stimulus and response is hard corded/hard wired. In this way, a crack in a typical type of self-healing polymer will, when reaching an embedded microsphere, induce it to crack and release its liquid content, which fills the crack tip region and hardens under the supporting influence of a catalyst embedded in the polymer matrix surrounding the microsphere. Thus the main difference between sensorial and self-X materials lies in the fact that the former are flexible in their reaction to a stimulus because they have the potential to actively evaluate it, they can adapt their knowledge about themselves and in consequence their response based on sensory information, and they can communicate the associated knowledge to other entities. In a sense, they have a potential for spatial and temporal self-awareness, and in contrast to self-X materials, they respond consciously, not spontaneously.

Basically, two ways may be envisaged to realize sensorial materials: one is top-down and the other is bottom-up [7]. The top-down approach develops sensor-equipped structures along the lines of miniaturization, compliant solutions for sensors, embedding techniques, and so on toward the point where they may be considered sensorial materials. The threshold implied between structure and material is hard to pinpoint: one indirect, practical approach at a definition is by stating that in a true sensorial material, the dimensioning to the primary (in our case mechanical) role should not be affected by any provision for the sensorial capabilities of the material. This is contradictory because it may be read to say there is no benefit to structural design brought about by sensorial materials. What is meant, however, is that the influence of embedded microsystems on mechanical performance should not have to be explicitly modeled in the sense of geometrically representing heterogeneity. Instead, sensorial materials should allow being treated as homogeneous materials rather than as hybrid structures. Homogeneous in this sense may include providing for local, stochastic property variations introduced or altered by embedded systems in a way similar to provisions of this kind nowadays made for composite materials.

It is obvious from this description that there is a close link between the ''smart dust'' concept and sensorial materials [8]. The envisaged smart dust particles, when embedded in, for example, a structural material, may be identified with the individual sensor nodes present in a sensorial material, while the envisaged size of a dust particle would allow fulfilling the homogeneity principle. Challenges, too, are very similar: in both cases, further miniaturization is an issue, and sensor nodes, such as smart dust particles, need to get by on as little energy as possible without losing their ability to communicate and process data [9]. Some aspects, although may favor the development of sensorial materials, for example, depending on host material and application, size reduction in one dimension may suffice in their case. Furthermore, the spatial relation between sensor nodes will be fixed in most sensorial materials, whereas it is dynamic in smart dust. Besides, the distinct position of components in a product made of a sensorial material will facilitate placement of energy-harvesting elements and render their potential yield more predictable in relation to known service cycles.

Summing up, sensorial materials thus turn out to be highly integrated, self-sufficient variants of smart or rather intelligent structures. Not surprisingly, this implies that development of true sensorial materials is highly interdisciplinary and involves several subordinate aspects. As a consequence, there is a multitude of research organizations that address one or more of the central aspects, but do not cover the entire field.

## 17.2 Components

Considering sensorial materials from the top-down perspective, development becomes a jigsaw puzzle in which different components have to be made to fit together on a new level of miniaturization and compliance with each other as well as the surrounding material or structure. Which components these are is exemplarily depicted in Figure 17.1.

Currently, sensorial materials are a vision with top-down approaches toward their development most likely to succeed within the next 5 or 10 years. Development of these materials will thus greatly depend on development of the individual components.

This is the justification of the chosen chapter substructure, which addresses the sectors sensors, component integration, data processing, and energy supply, including management and storage separately. Owing to the width of the field and the many disciplines involved, the level of detail will necessarily be limited and some highlights only brought to the full attention of the reader. These will be selected based on the specific relevance for the encompassing field of interest.

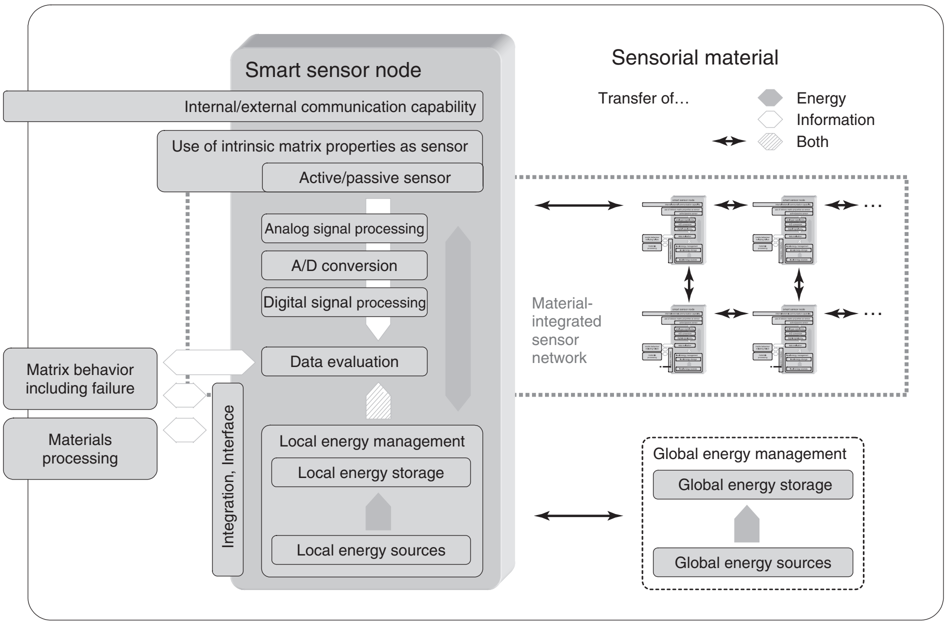



**Figure 17.1** Fundamental structure of a sensorial material, perceived as combination of a host material and an integrated network of smart sensor nodes. Added global energy supply, storage, and management are optional, as they constitute a deviation from the concept of homogeneity.

### 17.2.1
### Sensors

For the purposes of structural monitoring, sensors that detect damage or mechanical loads-the latter either directly or by their effects-, are of primary interest. Furthermore, for a true sensorial material, these sensors must provide a response that is accessible to further processing. Thus material concepts that rely on transferring the information of damage via ‘‘bruises’’ do not fall in this category, as they leave the interpretation of the – in this case, optical – signal to an external observer, be it a human being or an external technical system. In general, those types of damage sensors reporting the event in a binary manner via being destroyed themselves are of less interest to sensorial material technology. Here, data acquisition becomes a one-time event and quantitative interpretation at least difficult as the sensor response can only be interpreted in terms of a threshold value having been passed, but not in terms of at which height. Thus, indirect inference of damage, for example, based on quantitative strain sensing, and an internal description of the structure that relates sensor signal patterns to structural state are preferable.

Detection of mechanical strain fulfilling these requirements is commonly achieved by means of piezoelectric, piezoresistive, or optical sensors. Table 17.1 gives an exemplary overview of relevant optical sensor principles and relates some of their major characteristics based on a collection by Lopez-Higuera *et al.* [10].

**Table 17.1** Overview of commercially available optical displacement, strain, and pressure-sensing systems suitable for structural monitoring tasks with some characteristics, primarily based on Lopez-Higuera *et al.* [10].

| Basic principle | Sensor type | Resolution | Frequency/speed |
|---|---|---|---|
| Fiber Bragg grating (FBG) | Strain | 0.2 $\mu\varepsilon$ | Maximum 10 kHz |
| SOFO V | Displacement | 2 µm | Hz |
| SOFO dynamic | Displacement | 0.01 µm | 0–10 kHz |
| Brillouin scattering | Strain | 1 m | — |
| Fabry–Perot interferometry | Strain | 0.1 $\mu\varepsilon$ | Maximum 500 Hz |

Naturally, the concrete choice of sensors depends very much on host material and application requirements, such as required accuracy, sampling frequency, and long-term stability under service conditions. The standard choice for strain sensing today are either conventional strain gauges or fiber optic sensors working according to the principle of fiber-Bragg gratings (FBGs). Both are passive sensors that require a source of energy, either electrical or as light passing through the fiber. In fiber-reinforced polymer matrix composites (FRP), measurement of lamb wave propagation through the material with excitation based on piezoelectric transducers and signal detection realized according to the same principle is another method applicable for damage detection purposes (Chapter 8) [11].

Strain gauges detect strain via the piezoresistive effect, that is, the change in resistivity of a material subjected to mechanical strain. Their sensitivity depends on the material selected. It is lower in metallic conductors and significantly increased in semiconductor materials, the drawback being that in the latter case, temperature sensitivity is also increased, meaning that compensation of its effects must be considered. For this reason, alloys such as Cu55Ni44Mn1 are favored as they are temperature insensitive over a considerable temperature range around the ambient. They usually come on foil to be adhesively bonded to the structure to monitor. An alternative, more flexible approach is maskless printing [12], which can also be based on CuNi alloy inks [13, 14].

FBG-type sensors are easily integrated in carbon and specifically long glass fiber-reinforced composites. They can provide distributed, localized information about strain based on the possibility to integrate a multitude of sensors in a single fiber and still read them out individually. However, conventional solutions are limited to detecting only longitudinal strain, and besides need compensation for temperature-induced strain. The latter problem can be solved either by integrating additional, mechanically decoupled sensors of identical type or by introducing a secondary sensor network to capture the temperature field and use this information in data evaluation. The former aspect is addressed in present research efforts, which combine special, polarization-maintaining fiber buildups with a cross-sectional shape in which the inner core and thus the actual waveguide move out of the neutral axis in bending. This way, considering intensity and wavelength shift, both bending radius and orientation can be fixed. As a side aspect, the actual number of sensors needed for a given task that involves measurement of complex strain fields can be reduced, and spatial separation of the exact point of measurement of individual strain components avoided [15].

### 17.2.2
### Component Integration

Sensorial materials require sensors and peripheral devices, including energy supply and communication lines to be integrated into the material. This raises several technological issues, which can be roughly associated to the ability of devices to withstand the thermal and mechanical loads during production of the host material and its processing into a component, compliance with host material properties and, last but not least, the cost of integration versus its benefit for the product.

Integration is greatly facilitated if a sensorial material can be assembled from components for which sensor integration solutions exist. Examples are technical textiles, in which fiber-type sensors can be integrated either in the making of the textile, for example, during weaving [16], or by following this step, for example, by stitching [17]. The final material can then be realized as fiber-reinforced composite, for example, by resin infusion in processes such as resin transfer molding. Solutions of this kind have been discussed in the context of SHM in Chapter 6. As the references show, these techniques can provide for the sensor, but usually not for the peripheral elements.

The latter can be achieved if layered structures are integrated in a material that has, in itself, a layered buildup. Again this is the case with several types of fiber-reinforced composites. Examples exist for both dry fiber- and prepreg-based processes. The sensor elements themselves are commercially available, for example, by companies such as Accellent (SMART layer™), which rely on piezoelectric devices produced via printed circuit techniques for this purpose [18, 19]. Similar ''smart patch'' solutions exist for optical sensors, too [20].

An approach that goes beyond the SMART layer™ technique has recently been suggested by Hufenbach*et al.* for fiber-reinforced composites based on thermoplastic matrices. Piezoelectric sensors and actuators are provided on thermoplastic foils that match the composition of the matrix of the composite. In the composite buildup, these elements are placed between fiber layers (e.g., prepregs). During hot pressing, the supporting foil partially melts and guarantees a material integration, which is shown to outclass adhesive bonding in terms of transmission of strain [21].

For connecting such elements to form a sensor network, additional efforts are needed, irrespective of the communication being envisaged as wireless or based on physical connections. Printing techniques may provide one common solution for this problem, provided that a continuous layer exists within the material, which is accessible to such functionalization. In sheet-type materials, this is usually the case with the outer surface, leading to sensor application rather than to integration. In layered materials, however, true sensor integration may be achieved if the multilayer built-up is used to apply the sensor network to one of the internal layers.

Basic printing processes for sensor integration include maskless (aerosol jet printing and inkjet printing) as well as mask-based processes (screen printing and offset printing). Printing of various kinds of sensors, including strain gauges for detection of mechanical strain, has been demonstrated for both inkjet and aerosol jet processes as well as for screen printing. Differences lie in the achievable resolution, which goes down to approximately 10 µm and slightly below using aerosol jet printing, 20–50 µm for inkjet printing, and millimeter-sized structures for screen printing of metallic pastes – for other types of functional materials, screen printing too can reach higher resolutions. Later development in inkjet printing technology promises even higher resolutions of few micrometers and is reported to enable true three-dimensional (3D) structures, too [22, 23]. Substrates can be metals (if conductive structures are printed, this requires application of an insulating layer first, which is also possible), ceramic, and even textiles in the case of aerosol jet printing [12]. Roll-to-roll processes are of special interest when it comes to realizing large-area structures with high degree of detail, but nevertheless at low cost. Recently, offset printing has been applied to produce large-area electronic structures, including sensors, conductive paths, and data evaluation electronics. The advantageous flexibility of printing processes is not limited to freedom in geometry implied by their classification as direct-write processes (''art-to-part,'' i.e., direct realization of computer-generated models), but extends to the wide range of materials that can be processed, and based on it, a similar scope in terms of components. For example, energy storage devices such as batteries and capacitors as well as RFID antennae have been realized in this way [23, 24].

Generally, compliance of sensors with production and use is an important aspect. In terms of production processes, sensors need to be able to withstand the considerable thermal and mechanical loads associated with the making of a structural material. This explains why composites are presently leading the field. Here, both the thermal and the mechanical load are limited, and in many processes, the initial shape is also the final, as no subsequent forming is foreseen. However, first experiments with metal matrices have also been made. This includes rapid manufacturing approaches, as presented in Chapter 18, which have the general potential to facilitate component integration based on the layerwise buildup of structures typical for these techniques.

Besides, fiber metal laminates, which consist of alternating layers of sheet metal and fiber-reinforced composites, bear great promise for extending sensor integration to metallic materials, as they combine certain metallic performance characteristics with a consolidation process that essentially relies on polymer processing techniques: The thermal and mechanical loads which the integrated components have to endure and are thus greatly reduced.

How severe these conditions can be, and, on the other hand, the fact that they are nevertheless manageable, is exemplified by first approaches to integrate sensors, actuators, and energy-harvesting devices in light metal castings [25]. Metal integration of sensors generally tends to be the greater challenge as thermal and/or mechanical loads exerted on components to be integrated are usually higher. If casting is the prime example in this respect for the thermal case, so is metal

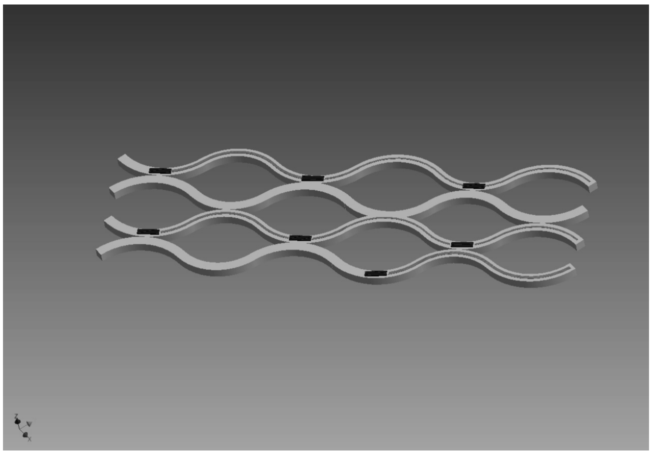


**Figure 17.2** A thermogenerator realized as functional net, shown here to illustrate this principle (image provided by Institute of Microsensors, Actuators, and Systems, University of Bremen). The wavy shape of remaining substrate and active components is meant to provide stretchability. Source: Image courtesy of Institute of Microsensors, Actuators, and Systems, University of Bremen.

forming with respect to mechanical stress. If the latter is dominant, flexibility and stretchability of all embedded elements is needed – or, as this may not be achievable in most cases, at least of their interconnects. Positioning the components in the neutral plane can be an alternative, but depends on processing and service loads allowing such measures. Besides, it may not be advisable for the sensor itself, which is expected to see some signal after all. Progress in this field will provide further support for sensorial material development. Several approaches to realize compliance have been discussed by Lang *et al.* [7]. Besides materials characteristics, in many cases, geometries are adapted. Figure 17.2 depicts a thermogenerator for integration with castings, which represents this approach. Here, the aim is to accommodate thermal expansion or rather contraction during cooling of the cast part. Solutions for sheet metal integration of piezoelectric sensors and actuators based, for example, on microforming of cavities in sheet metals, meant to take up the active elements, have been suggested by Neugebauer *et al.* [22], and their capability to serve as a semifinished product that can sustain limited degrees of forming to generate a product shape demonstrated.

Had all integration-related issues been solved, material-embedded sensor networks would still remain a wound within the host material. For this reason, reduction in size is required. Lang *et al.* [7] have coined the term *function scale integration* for this approach. The size of sensors and peripheral elements and thus the footprint they leave in the material are to be reduced to the absolute minimum needed to guarantee the respective element functionality. Progress in this area is very much influenced by packaging technology, and the development of RFID techniques and smart card solutions have brought about several breakthroughs in this respect. Table 17.2 provides an overview of sensor ''footprints,''

**Table 17.2** Footprint associated with pressure sensor integration as a function of progress in packaging technology [7].

| Packaging technology/housing type | Volume ($mm^3$) | Footprint ($\mu m$) | Approximate year of introduction |
|---|---|---|---|
| Silicon chip in TO8 housing | 300 | 10 000 | 1990 |
| Dual-in-line (DIL) package | 100 | 500 | ↓ |
| Chip size package | 20 | 3000 | ↓ |
| Capacitive pressure sensor chip, surface micromachining | 0.2 | 500 | ↓ ↓ |
| RFID chip, thin chip technology | 0.025–0.2 | 400–2000 | ↓ |
| Perforated chip functional net | 0.05–0.4 | 40 | 2010 |

comparing similar functionality – in this case pressure sensing – and the influence of packaging technologies that reflect the development progress in recent decades and years. Note that *footprint* in this case is defined as the greatest continuous extension of the component in a critical spatial dimension.

Looking at the sensor and classical microsystem technology approaches, the next step will be to further reduce substrate volume to create functional nets, as depicted in Figure 17.2 [7].

### 17.2.3 Data Processing: Algorithms and Hardware Architectures

The major motivation behind the defining requirement of internal data evaluations toward sensorial materials is the understanding that only concepts based on localized data processing will be able to provide real-time evaluation of a structure's state. Besides, distributing data processing may reduce vulnerability to damage and increase robustness and fault tolerance of a sensorial material.

Recently, emerging trends in engineering and microsystem applications such as the development of sensorial materials pose a growing demand for active networks of miniaturized smart active sensors embedded in technical structures [23, 24]. Each sensor node consists of some kind of physical sensor, electronics, data processing, and communication, providing a certain level of autonomy, dynamic behavior, and robustness [29].

With increasing miniaturization and sensor density, decentralized network and data-processing architectures are preferred or required. Spatial data fusion can be used to extract desired structural or temporal information, rather than to collect a large set of data, finally processed by a central data-processing unit.

Initially, independent data-processing nodes of a sensor network can be coupled using message-based communication enabling distributed computing capabilities. In the context of sensorial materials, 2D grid networks are suitable, shown in Figure 17.3. This network topology connects each node with up to four neighbor

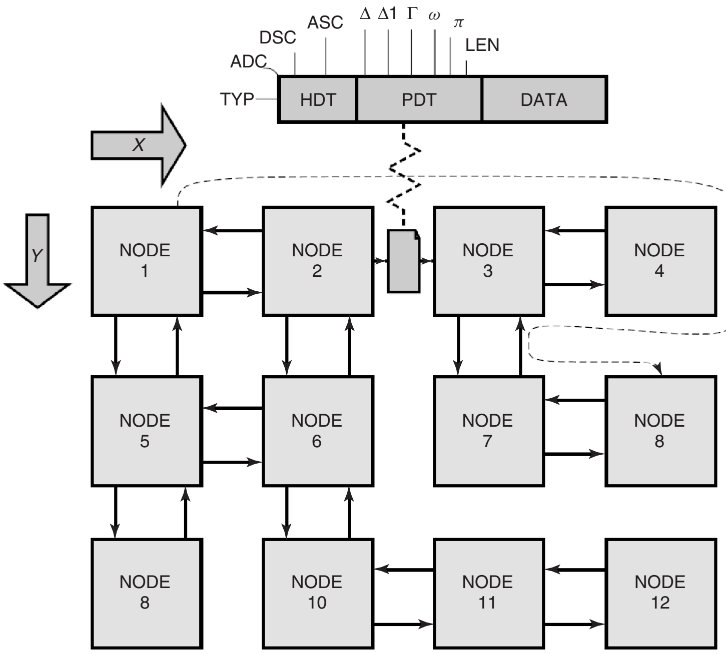



**Figure 17.3** An example of an irregular two-dimensional network using point-to-point link connections for message transfer. Each node is a service endpoint and router, too [30]. A message consists of a header descriptor HDT, a packet descriptor PDT, and the data part.

nodes. Interconnection dependencies between nodes are limited to a small local area, a prerequisite for high-density sensor networks embedded in materials. The network topology can be irregular, for example, depending on design or because of temporary failures or permanent physical defects of the existing communication links. Smart routing can be used to deliver messages on different alternative routes around partially connected or defective areas. An example of a fault-tolerant message-based communication system is the scalable local intranet protocol (SLIP) [30], which is discussed later. Nodes are able to send messages to a destination node using relative delta-addressing, avoiding unique node address identifier assignments, not applicable to nodes in high-density sensor networks.

Traditionally, embedded systems are composed of generic processor systems and peripheral components. Usually, generic processor systems have limited concurrency and power management capabilities. Application-specific single-chip digital logic circuits can overcome those limitations. The design and modeling of digital logic on hardware level is limited to less complex systems. Complex algorithms can only be mapped to digital logic systems using high-level synthesis on behavioral programming level.

For example, the ConPro development framework [31] enables high-level synthesis of parallel and distributed embedded systems on behavioral level. An imperative programming model is provided, based on concurrently communicating sequential processes (CSP) with an extensive set of inter-process communication primitives and guarded atomic actions preventing and resolving resource-sharing conflicts. The programming language and the compiler-based synthesis process enable the design of constrained power- and resource-aware embedded systems on register-transfer level (RTL) efficiently mapped to FPGA and ASIC technologies. Concurrency is modeled explicitly on control- and data path level.

There are local and global resources (storage, IPC), accessed by one process and several processes, respectively. Concurrent access of global resources is automatically guarded by a mutex scheduler, serializing access, and providing atomic access without conflicts. Figure 17.4 gives an overview of building blocks and the design flow using high-level synthesis. The multiprocess model provides concurrency on control path level using concurrently executing processes, and on data path level using bounded program blocks. Parallelism available on process level requires inter-process communication and parallelism available on data path level can be applied to arbitrary sequences of data path instructions bounded in basic blocks within a process. In addition, the high-level programming level can be used to synthesize software designs using the same compiler providing the same functional behavior as the hardware design.

The main synthesis flow transforms and maps process instructions to states of clock-synchronous finite-state machines (FSMs) controlling the process RTL data path temporally and spatially, shown in Figure 17.4c.

Abstraction of hardware components, implementing, for example, device drivers, is provided by the external module interface (EMI), closing the gap between the software and hardware levels. The EMI encapsulates hardware components with abstract objects, visible on programming level. Objects can only be used and modified using method operations applied to these objects.

Many systems and algorithms used in sensor networks can be explicitly partitioned into communicating concurrently executing processes using the previously described programming model and design methodology.

Figure 17.5 shows an example, which is the multiprocess architecture of the SLIP protocol stack implementing the router of a sensor node. A sensor node is able to communicate with four neighbor nodes, arranged in the network topology shown in Figure 17.3. Both incomplete (missing links) and irregular networks (with missing nodes and links) are supported for each dimension class using a set of smart routing rules.

The path from a source to a destination node is specified by a delta-distance vector. A delta-distance vector $\Delta$ specifies the way from the source to a destination node counting the number of node hops for each dimension (known as *XY routing*).

The SLIP protocol and message format are scalable with respect to network size (extension in each dimension), maximal data payload length, and the network topology dimension size. A message packet contains a header descriptor specifying the type of the packet and the scalable parameters, followed by a packet descriptor containing the actual delta-vector $\Delta$, the original delta-vector $\Delta^0$, a preferred routing direction $\omega$, an application layer port $\pi$, a backward-propagation vector $\Gamma$, and the length of the following data part.

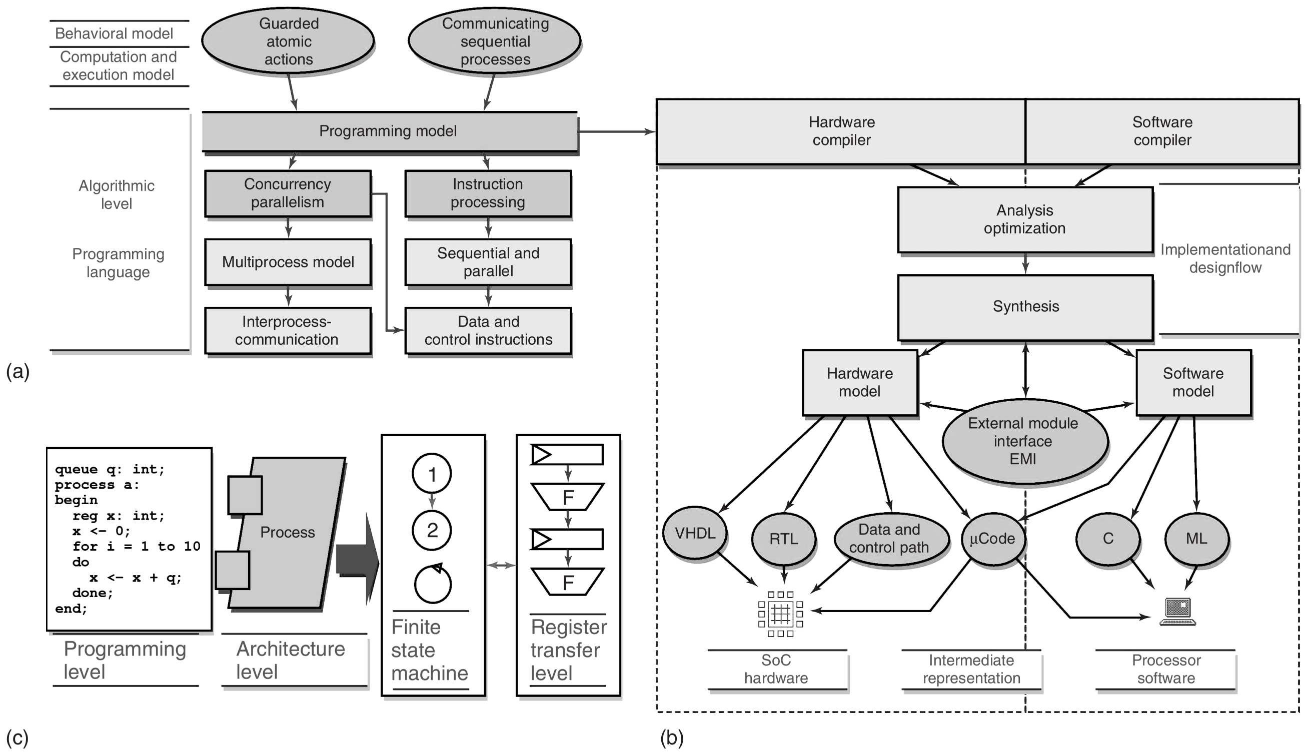



**Figure 17.4** Building blocks of the programming model (a), the high-level synthesis (b), mapping the programming level to digital logic using RTL architecture (c).

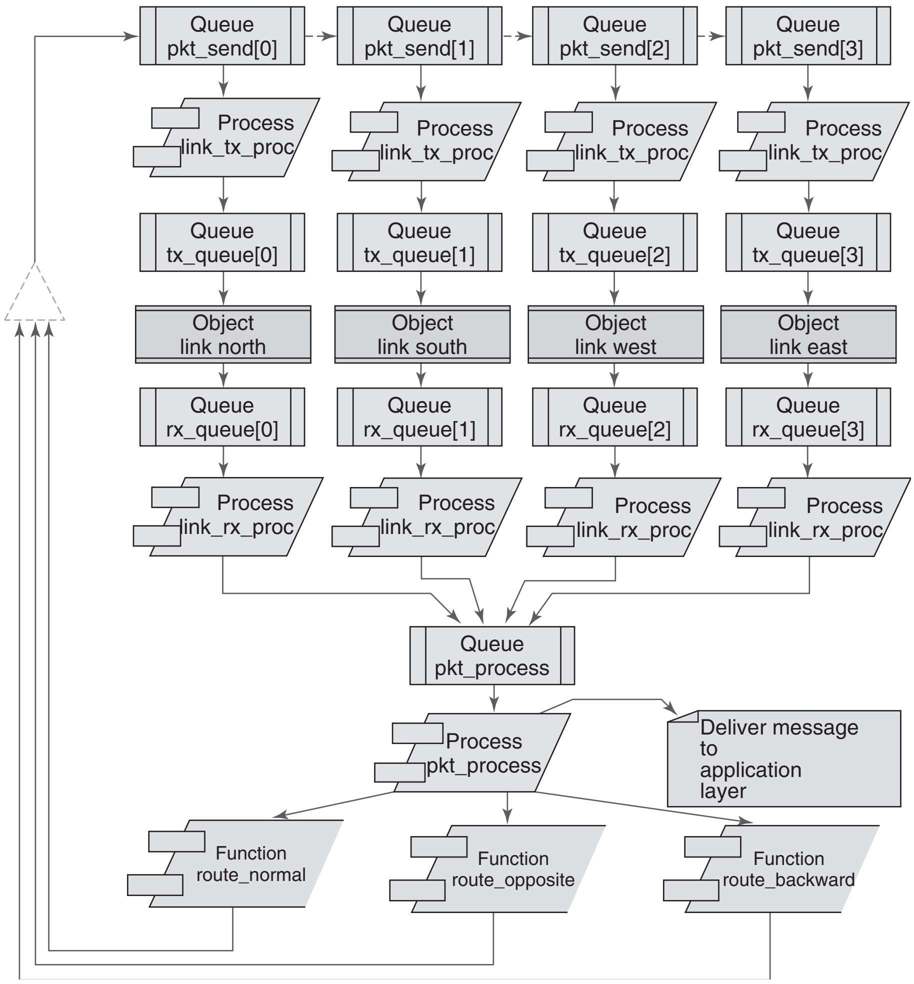



**Figure 17.5** Process and inter-process communication architecture of the SLIP protocol stack.

Although the protocol stack is implemented entirely in hardware, it is modeled on high algorithmic level, shown in simplified form in Algorithm 17.1. First, the normal XY routing is tried, where the packet is routed in each direction one after another with the goal to minimize the delta count of each particular direction. If this is impossible (due to missing connectivity), the packet is tried to send to the opposite direction, marked in the message packet descriptor. Opposite routing is used to escape small-area traps; backward routing is used to escape large-area traps or send the packet back to the source node (packet not deliverable). Link and message-processing paths are implemented concurrently using sequential executing processes interchanging data using queues for inter-process communication.

**Algorithm 17.1 Smart routing protocol SLIP (simplified)**

```
M:  Message(Δ,Δ⁰,Γ,ω,Π,Len,Data)
PRO smart_route(M):
   IF Δ=0  THEN  DELIVER(M,π) ELSE
   TRY  route_normal(M)  ELSE
   TRY  route_opposite(M)  ELSE
   TRY  route_backward(M)  ELSE  DISCARD(M);
PRO route_normal(M):
   FORONE δi ∈ Δ TRY minimize δi :
    route(Δ,M)  WITH δi:=(δi+1)|δi<0 ∨ (δi−1)|δi>0;
PRO route_opposite(M):
   FOREONE δi ∈ Δ TRY minimize δi :
     route(Δ,M)  WITH δi:=(δi−1)|δi<0 ∨ (δi+1)|δi>0;
PRO route_backward(M):
   SEND  M (received  from  direction δi)
     back  to  direction −δi WITH Γi=−δi/|δi|;
```

A comparison of traditional XY and smart routing using the routing rules is shown in Figure 17.6. The diagram shows the analysis results of operational paths depending on the number of link failures. A path is operational (reachable) if and only if a node (device under test), for example, node at position (2,2), can deliver a request message to a destination node at position $(x,y)$ with $x \neq 2 \wedge y \neq 2$, and a reply can be delivered back to the requesting node. A failure of a specific link and node results in a broken connection between two nodes. Figure 17.6b shows an incomplete network with 100 broken links.

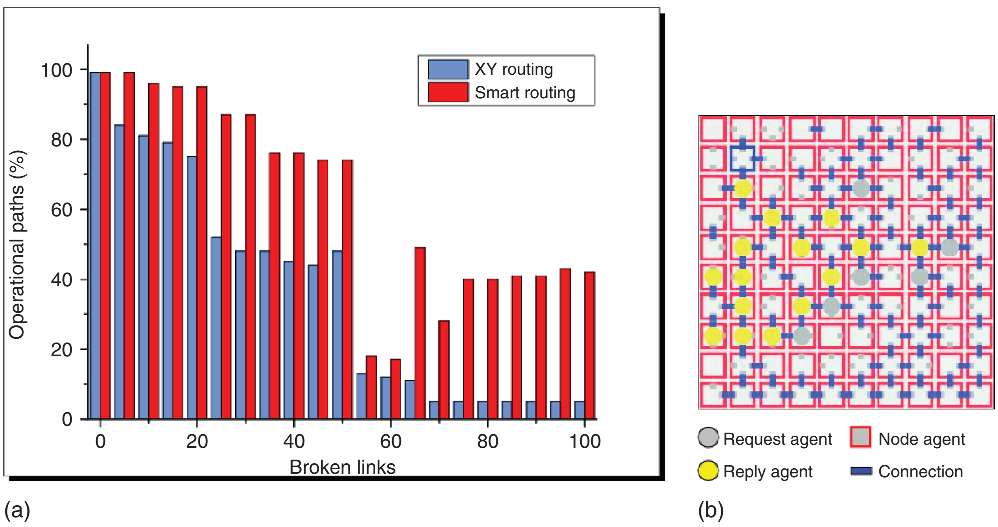



**Figure 17.6** Robustness analysis with results obtained from simulation (a) and snapshot of sensor network (b).

With traditional XY routing, there is a strong decrease in operational paths, from a specific node (DUT) to any other node, if the number of broken links increases. Using smart routing increases the number of operational paths significantly, especially for considerable damaged networks, up to 50% compared with XY routing providing only 5% reachable paths any more.

The hardware implementation (using ConPro and standard cell ASIC synthesis) requires about 244k gates, 15k FF 2.5 $mm^2$ assuming ASIC standard cell technology of 0.18 µm. The design is partitioned on programming level in 34 processes, communicating using 16 queues.

### 17.2.4
### Energy Supply and Management

Offering sufficient amounts of energy to the right sensor network node at the right time is a central issue for sensorial materials. Its main aspects are provision, storage, distribution, and management of energy. The supply itself can be based on external sources, energy storage devices, energy harvesting, or a combination of these three. From entirely local to centralized generation and storage, everything is possible, as are the many conceivable intermediary solutions. In practice, combinations of the latter two dominate, which usually implies a need for intelligent management of resources both in time and in space.

Energy storage on the microscale relies mostly on thin film batteries and capacitors. While the former generally provide higher energy densities, the latter excel in power density, but suffer from leakage currents that prevent efficient long-term power storage. Other concepts include microscale fuel cells or even miniaturized internal combustion engines, both of which need a reservoir for the energy carrier and are thus considered more exotic solutions – the more so because in their case the combination with energy harvesting, which typically provides electrical energy (see below), is difficult to realize. An overview covering the full variety of smaller scale energy system concepts has been provided by Krewer [32]. Among the microfuel cells specifically, proton exchange membrane fuel cells (PEMFCs, PEMµFC) and direct methanol fuel cells (DMFCs, DMµFC) prevail. An overview of both is given by Nguyen and Chan [33], while DMFC developments are highlighted by Kamarudin *et al.* [34].

Thus for sensorial materials, the focus is mostly on electrical and electrochemical energy storage systems and thus microbatteries, capacitors, and nowadays certain intermediary or hybrid systems, all of which are usually realized as thin film devices. With typical thicknesses in an order of magnitude below 100 µm, their achievable storage capacity and power output are often expressed per unit area. Table 17.3 provides a comparison of typical systems, adding selected data on fuel cells as further example. The dominant technical solution in terms of batteries are Li-ion-based concepts, which currently provide the best combination of many practical aspects, including besides energy density high numbers of charging/discharging cycles achievable. According to Patil *et al.*, the energy content for Li ion systems will reach saturation levels at approximately 220 Wh $kg^{-1}$ and 530 Wh $l^{-1}$ [35]. Thin

**Table 17.3** Battery systems as energy storage solutions for microscale power supply compared. Note that units of power density vary throughout the table, with the heading giving the prevalent one for each case.

| Type of storage device | Voltage | Energy density | | Power density | References |
|---|---|---|---|---|---|
| | (V) | (Wh $kg^{-1}$) | (Wh $l^{-1}$) | (kW $kg^{-1}$) | |
| Batteries | | | | | |
| Ni–Cd | 1.2 | 40 | 100 | — | [35] |
| Ni metal hydride (MH) | 1.2 | 90 | 245 | — | [35] |
| Ag–Zn | 1.5 | 110 | 220 | — | [35] |
| Li ion | 3.6 | 155 | 400 | — | [35] |
| Li- polymer | 3.6 | 180 | 380 | — | [35] |
| Li thin film | 3.6 | 250 | 1000 | — | [35] |
| Capacitors | | | | | |
| Activated carbon/$PbO_2$/ sulfuric acid | 2.25–1.0 | 15.7 | 39.2 | 8.9[a] | [36] |
| Activated carbon/NiOOH/ KOH | 1.6–0.6 | 13.9 | 31.5 | 4.0[a] | [36] |
| $Li_4Ti_5O_{12}$/activated carbon/acetonitrile | 2.8–1.6 | 13.8 | 24 | 3.8[a] | [36] |
| Advanced carbon/advanced carbon/acetonitrile | 3.3–2.0 | 13.7 | 19 | 1.9[a] | [36] |
| Activated carbon/activated carbon/sulfuric acid | 1.0–0.5 | 1.72 | 2.2 | 1.2[a] | [36] |
| Activated carbon/activated carbon/acetonitrile | 2.7–1.35 | 5.7 | 7.6 | 6.4[a] | [36] |
| Microfuel cells[b] | | | | mW $cm^{-2}$ | |
| Proton exchange membrane fuel cell (PEMFC) | 1.23 | — | — | Up to 315 mW $cm^{-2}$ | [33] |
| Direct methanol fuel cell (DMFC) | 1.21 | — | — | Up to 100 mW $cm^{-2}$ | [33] |
| DMFC | 1.21 | — | — | 43 mW $cm^{-2}$ | [34] |

[a] 95% efficiency according to [36].
[b] Note that it is difficult to specify energy density for fuel cells, as energy transduction and storage of the energy carrier are separated and thus a larger fuel capacity will push the figure to higher values, with the energy content of the fuel usable based on the efficiency of the process as upper limit.

film systems may exceed these values, as shown in Table 17.3. Note however that for Li ion batteries, improvement of energy and power density usually is conflicting aims.

Recently, 3D structuring of batteries has received renewed interest. This approach should not be misunderstood as a mere stacking of planar thin film batteries in the third dimension. In contrast, structuring takes place within the cell at the nano- and microscopic levels and allows improvement in performance-controlling characteristics such as the electrode–electrolyte interface area or the effective thickness of electrode and electrolyte layers, thus, for example, reducing otherwise power-limiting diffusion path lengths.

The resulting components may remain as thin film, but their energy and power density can be stepped up significantly at the same real footprint. The potential of the method has been repeatedly demonstrated, for example, by Ho *et al.* [23] based on inkjet-printed Ag–Zn microbatteries, in which a comparatively wide spacing of printed silver pillars providing electrode structuring led to an increase in the areal energy density to 3.95 from 2.33 Wh $cm^{-2}$, observed for a planar-silver-electrode-based buildup produced by means of the same super inkjet printing process. Similarly, increases by an approximate factor of 5 depending on aspect ratio of electrode-structuring trenches and pores have recently been published by Baggetto *et al.* [37] for poly-Si-based negative electrodes to be used in Li ion batteries.

Detailed reviews on recent work and potentials of 3D structuring techniques applied to microbatteries have been published by Long *et al.* [38] and more recently by Roberts *et al.* [39] and Oudenhoven *et al.* [40]. The investigated systems are usually Li ion variants, with both solid and liquid electrolyte concepts addressed.

In terms of systems under study, another special focus is on Li-based solutions using solid-state electrolytes. Challenges in this field have been summarized by Patil *et al.* [35] and include the identification of candidate electrolytes providing sufficient Li ion conductivity. The latter is of specific significance as otherwise the internal resistance of the cell will produce an unwanted limitation to power output. High-conductivity electrolyte materials would thus complement structuring approaches aimed at maintaining the low conductive path length (equivalent to electrode layer thickness) typically realized in planar thin film systems.

Besides structural optimization and search for improvement in active materials, additional efforts are directed at alternative material systems, that is, at alternatives in terms of the fundamental reaction enabling energy storage and retrieval. Because of their promise for high energy density, which has its theoretical limit about an order of magnitude above conventional lithium ion systems, lithium–oxygen batteries receive special attention in this context. However, despite their attractive performance, their applicability to sensorial materials may turn out to be limited as their fundamental principle of operation implies access to air or at least a suitable source of oxygen, which may contradict the need for embedding of systems in a host material to ensure durability. Research on the system as such is driven by the need for breakthrough energy storage solutions for future electric vehicles. Currently, many technological challenges remain, and so far no functional full cell has been realized. The state of research is outlined by Cheng and Chen [41], Christensen *et al.* [42], and Bruce *et al.* [43].

Development of capacitors mirrors exertions in the field of batteries in as far as the alleviation of typical weaknesses is addressed. For capacitors, this is energy rather than power density. The focus is on electrochemical capacitors, which replace the dielectric separating the electrodes in conventional capacitors with an electrolyte. Two fundamental storage mechanisms can be distinguished. In electrochemical double-layer capacitors (EDLCs), charge storage is electrostatic based on reversible adsorption of electrolyte ions on the oppositely charged electrode's active material surface. High levels of capacity are basically enabled by large active material surfaces (e.g., porous or nanostructured carbon- and materials) and by the small distance between opposite charges in the double layers at each electrode. Charging and discharging can be extremely fast, as no chemical reaction kinetics have a part in energy storage. Recent developments to further improve energy density include nanoporous active materials with pore sizes tailored to match sizes of charge-carrying ions as some studies suggest that such morphologies can partially remove solvation shells surrounding these ions in the electrolyte, resulting in smaller effective size and thus a higher density of charger carriers on the double layer's electrolyte side [44].

Redox-based electrochemical capacitors showing pseudocapacitive charge storage form another class of electrochemical capacitors. In their case, fast and reversible redox reactions occur at the active material surface, which is very often a metal oxide such as $RuO_2$, $Fe_3O_4$, or $MnO_2$. Specific capacitance observed exceeds that of EDLCs, but as chemical reactions are involved, reaction kinetics can limit power output, and the advantageous characteristics of electrostatic processes in terms of cycling stability can suffer [44].

As finding the right balance between energy and power density is central for optimized energy storage, attempts at combining the two fundamentally different concepts of batteries and capacitors deserve attention. The resulting hybrid capacitors usually combine a capacitor electrode with a battery one, at the cost of a certain amount of power density, but naturally with benefits for energy storage capacity. The concept can facilitate increased cell voltage, too, which affects both energy and power density favorably. A drawback is the fact that cyclability, one of the mainstays of capacitors besides their superior power density, can suffer in hybrid designs [44].

As future sensorial materials will have to stay functional over a considerable service life without much possibilities for maintenance, energy supply is unlikely to be feasible based on storage and thus primary batteries alone. Therefore, secondary or rechargeable systems have been the focus of the preceding discussion. The answer to the question where the energy for recharge should originate from may be twofold. Need-based recharging from external sources following extended service cycles is an option – however, as outmost autonomy of sensor networks in sensorial materials is a major aim, internal energy generation and thus energy scavenging or harvesting is a central issue in their development. Generally, energy harvesting means tapping energy sources from the environment to match a system's requirements. Major principles that can be used are harvesting of

- thermal energy (e.g., thermoelectrics and Seebeck effect);
- vibration energy (e.g., piezoelectrics);
- light (e.g., photovoltaics);
- radio frequency electromagnetic radiation;
- fluid flow.

**Table 17.4** Overview of ambient energy sources here for the tapping by means of energy-harvesting devices, approximate data collected by and according to Yildiz [45] and Valenzuela [46].

| Ambient energy source | | Technical principle[a] | Approximate power density | | Typical efficiency[b] |
|---|---|---|---|---|---|
| **Class** | **Subclass** | | ($\mu W\,cm^{-2}$) | ($\mu W\,cm^{-3}$) | (%) |
| Light | Outdoor | Photovoltaic | $10^5$ | n.a. | 10–24 |
| | Indoor | Photovoltaic | 100 | n.a. | 10–24 |
| Thermal | Human | Thermoelectric | 60 | n.a. | 0.1 |
| | Industrial | Thermoelectric | $10^3$–$10^4$ | n.a. | 3 |
| | Temperature variation | — | n.a. | $10^1$ | — |
| RF | Ambient RF | — | 1[a] | n.a. | — |
| | GSM 900 MHz | — | 0.1[b] | n.a. | 50 |
| | WiFi | — | 0.001[b] | n.a. | 50 |
| Vibration | Human (Hz) | Microgenerator | n.a. | 4 | 25–50 |
| | Industrial (kHz) | Microgenerator | n.a. | 800 | 25–50 |
| | — | Piezoelectric | n.a. | 200[a] | 25–50 |
| Acoustic | Acoustic noise, 75 dB | — | n.a. | 0.003[a] | — |
| | Acoustic noise, 100 dB | — | n.a. | 0.96[a] | — |
| Airflow | — | — | 1[a] | n.a. | — |

[a] Exclusive source: [45].
[b] Exclusive source: [46], all others [45] and [46].

Table 17.4 provides a rough estimate of the available energy per unit volume or area for several such solutions.

Energy harvesting solutions often rely on smart materials, such as thermo- or piezoelectric materials, with energy-transduction capability. In many cases, when microdevices are sought for, these are integrated in microsystems using MEMS and related technologies. The active materials themselves profit from new developments in nanostructures and low-dimensional architectures. Thermoelectrics are an example in this respect. In many relevant materials, for example, nanograined structures have been demonstrated to perform favorably in comparison to conventional materials as phonon scattering at grain boundaries allows influencing thermal and electrical conductivities independently. This opens up possibilities to lower the former while retaining the latter, a path that leads to increased efficiency in thermoelectrics.

Furthermore, theoretical work as well as early experimental validations for 2D quantum wells in PbTe-type materials by Dresselhaus *et al.* has long since provided evidence that low-dimensional structures can lead to performance increase [47]. Among many others, Davila *et al.* [48] have demonstrated this fact for Si nanowires in contrast to bulk Si, at the same time realizing major steps from fundamental material characterization toward working microscale thermogenerators using MEMS techniques. Developments in nanocomposite thermoelectric materials are partly aimed at utilizing related effects [49]. In terms of material classes in general, even though highest figures of merit (thermoelectric efficiency) are still documented for classical systems such as PbTe or BiTe, there is a tendency toward identifying alternatives that are less critical in terms of stability at elevated temperatures, environmental concerns, cost and so on, like many oxide materials [50].

Vibration energy harvesting is mostly based on piezoelectric materials and MEMS techniques for production of generators. Highest efficiencies are generally achieved if vibrating systems, for example, comprising a beam with attached mass can be tuned to the excitation frequency to work in resonance mode. However, this implies peak performance at a fixed frequency, which may not be ideal where vibration is randomly distributed over a larger frequency range. For this reason, wide bandwidth or even frequency-adaptable generators are being investigated [51]. Further approaches combine the sensor function with energy supply, that is, by deducing sensory information from the harvested energy flow. Systems of this kind relying on special zigzag metal counter-electrode designs to gather charges from flexed ZnO nanowires have been suggested by Wang *et al.* [52, 53], with improvements expected from transferring the basic concept to nanowires showing higher piezoelectric efficiency and thus a higher current yield than reported by Wang *et al.*, such as $BaTiO_3$ [54].

In terms of materials, the brittle behavior of many piezoelectric ceramics such as lead zirconate titanate (PZT) has fueled interest in polymers with generally comparable properties, and in piezoelectric composites. In the latter, active ceramic particles are embedded in a polymer matrix that addresses the concern in terms of mechanics [55], while at the same time facilitating processing of the materials, including techniques such as mask-based [56], but also maskless printing.

General overviews covering different types of energy-harvesting systems in conjunction with sensor and sensor network energy supply have recently been put together by Vullers *et al.* [57], who add information about power management circuitry, while Bogue [54, 58, 59] includes storage techniques in his reviews, too. Table 17.5 provides a glimpse at energy issues of systems that have recently been proposed in the application context of structural monitoring. A more detailed overview of energy-harvesting systems was provided by Hudak and Amatucci [60] in 2008.

Having thus discussed ambient and local energy availability and associated transduction, the issue of adequately using it in distributed sensor networks, and thus the consumer perspective, remains.

With increasing miniaturization and sensor density, decentralized energy supply using self-powered architectures is preferred. Energy harvesting, for example, using thermoelectrical sources, actually delivers only low electrical power, requiring (i) smart energy management on the consumer side controlling the energy consumption and (ii) low-power capabilities and design of sensor nodes.

**Table 17.5** Characteristics of selected sensor nodes suggested for structural monitoring applications, focusing on aerospace, with and without energy harvesting solutions implemented.

| Description | | | | Power | | | References |
|---|---|---|---|---|---|---|---|
| Application | Harvester | Storage | Sensor principle | System requirement (μW) | Provision[a] (μW) | System efficiency (%) | |
| Aircraft wireless sensor node for structural load monitoring | TG, combined with PCM | Cap., 1.8–2 F | Crack wire | 189[b] | 6000 | Approximately 0.05[c] | [61] |
| Credit-card-sized smart tag sensor node for aerospace applications | PEG, thick film printed | Cap., 0.55 F, 4.5 V | Temperature and pressure sensor, accelerometer | 88 900[d] | 240 | — | [62] |
| Autonomous sensor node in distributed wireless sensor network | None | Primary battery | Impedance sensor | 150 (sleep)<br>18 000 (active) | n.a. | — | [63] |
| RF-powered wireless sensor node | RFG | Cap., 2.2 mF | Strain gauge | 6000 | ~3801 | 52[e] | [64] |
| Wireless sensor node for guided wave-based SHM | None | LiPo primary battery | Guided wave propagation, piezoelectric excitation | 1399 mW (active),<br>50 mW (inactive) | n.a. | — | [65] |

[a] Power as supplied by harvesting unit under typical or design conditions of usage, prior to power conditioning an similar measures such as DC–DC conversion.
[b] Excluding communication requirements.
[c] Direct system efficiency, storage efficiency not included.
[d] Including communication and sensor power requirements.
[e] RF-to-DC conversion efficiency only, no full system efficiency.
Harvesting: PEG = piezoelectric Generator, PCM = phase change material for latent heat storage, RFG = radio frequency generator.
Electrical energy storage: Cap. = capacitor.

Advanced design methodologies for embedded systems can aid to satisfy low-power requirements targeting self-powered sensor nodes. Contributions to energy management are:

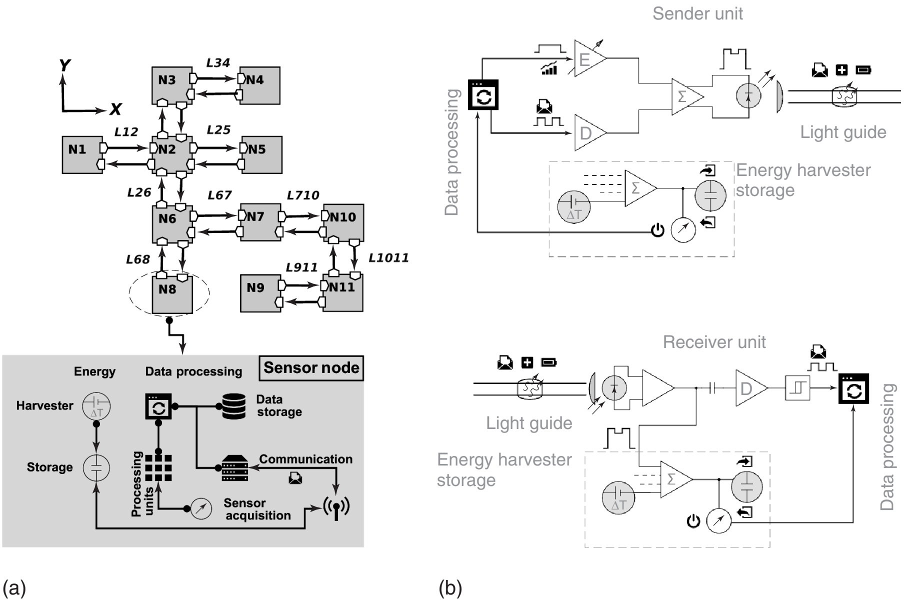
1. *Local smart energy management* performed at runtime using advanced computer science algorithms (artificial intelligence) providing optimization of power consumption.
   In contrast to various other approaches targeting algorithms and architectures with high computational effort, for example [66], *smart energy management* can be performed spatially at runtime by a selection from a set of different (implemented) algorithms classified by their demand of computation power, and temporally by varying data-processing rates. It can be shown that power/energy consumption of an application-specific system-on-chip (SoC) design strongly depends on computation complexity [67].
2. Optimized application-specific SoC design on RTL using high-level synthesis. Low-power systems can be designed on algorithmic rather than on technological level. Averaged SoC cell activity correlates strongly with computation and signal/data flow [67].
3. *Smart energy distribution* management in decentralized self-powered sensor networks using distributed artificial intelligence concepts and algorithms, such as multi-agent systems [68].

Sharing of one interconnect medium for both data communication and energy transfer significantly reduces node and network resources and complexity, a prerequisite for a high degree of miniaturization required in high-density sensor networks embedded in sensorial materials. Point-to-point connections and mesh-network topologies are preferred in high-density networks because they allow good scalability (and maximal path length) in the order of $O(\log N)$, with $N$ as the number of nodes.

Figure 17.7 shows the main building blocks of a self-powered sensor node, the proposed technical implementation of the optical serial interconnect modules, and the local energy management module collecting energy from a local source, for example, a thermoelectric generator, and energy retrieved from the optical communication receiver modules.

The data-processing system can use the communication unit to transfer data (D) and superposed energy (E) pulses using a light-emitting or laser diode. The diode current, driven by a differential-output sum amplifier, and the pulse duration time determine the amount of energy to be transferred. The data pulses have a fixed intensity several orders lower than those of the adjustable energy pulses. On the receiver side, the incoming light is converted into an electrical current using a photodiode. The data part is separated by a high-pass filter, and the electrical energy is stored by the harvester module.

Information and energy is encapsulated in messages routed in the network from a source to a destination node, using a simple delta-routing protocol. An alternative, advanced smart routing protocol, which allows incomplete mesh-networks and compensates link failures using different routing rules, is described in [30].




(a) (b)

**Figure 17.7** Network topology (a) and sender and receiver blocks (b) used for data and energy transmission between neighbor nodes. Each node connects up to four neighbors and uses optical links to transfer data messages and energy.

Using those technical abilities, it is possible to use active messaging to transfer energy from good nodes having enough energy toward bad nodes, requiring energy. An agent can be sent by a bad node to explore and exploit the near neighborhood. The agent examines sensor nodes during path travel or passing a region of interest (perception) and decides to send agents holding additional energy back to the original requesting node (action). Additionally, a sensor node is represented by a node agent, too. The node and the energy management agents must negotiate the energy request.

Some simulation results are shown in Figure 17.8, showing the benefits of energy management using multi-agent systems to negotiate energy demand and distribution using communication links for transmission of both messages and energy [69]. Each node is initially supplied by energy locally harvested and stored in an energy deposit. Without energy management, there are nodes with insufficient energy. Using smart energy management, all nodes can be supplied with enough energy to fulfill data and message processing.

## 17.3 Case Study

In this section, a case study of the modular robot arm manipulator project ModuACT is presented, showing the integration of sensorial materials in robotics [70].

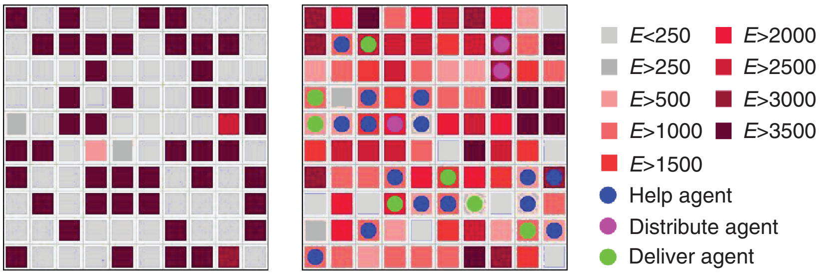



**Figure 17.8** Results from multi-agent simulation without and with energy management. Help, deliver, and distribute agents are used to compensate low-energy nodes (blue color). Sensor nodes can exchange messages (agents) and energy using communication links.

An active sensor network embedded in the connection structure of a robot arm manipulator is used to provide load and touch perception of the environment, shown in Figure 17.9. It features locally tight coupling and integration of sensors, actors, and data processing and communication, and globally decentralized data processing with a network of distributed sensor nodes embedded in the robot arm structure.

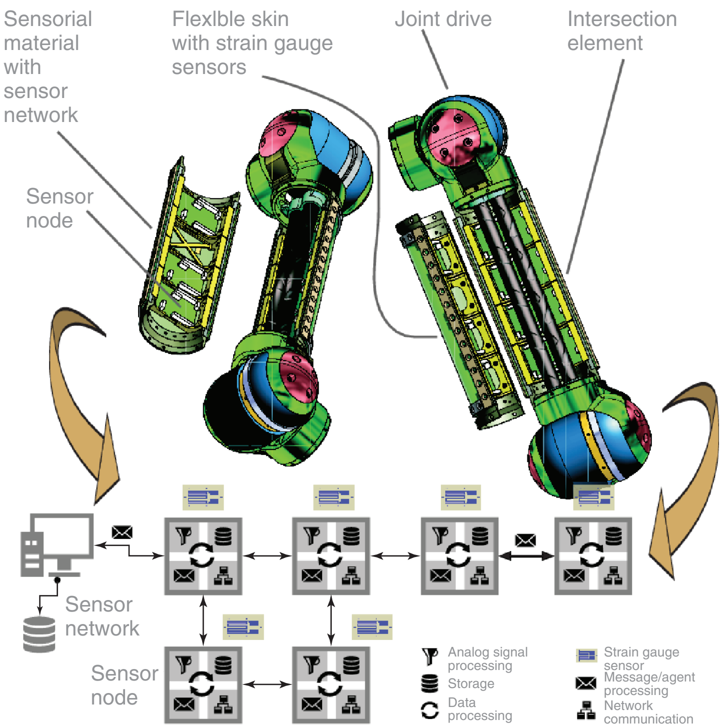



**Figure 17.9** A robot arm manipulator featuring a network of sensorial materials and actuator joints. The intersection structures integrate a sensorial material for environmental perception.

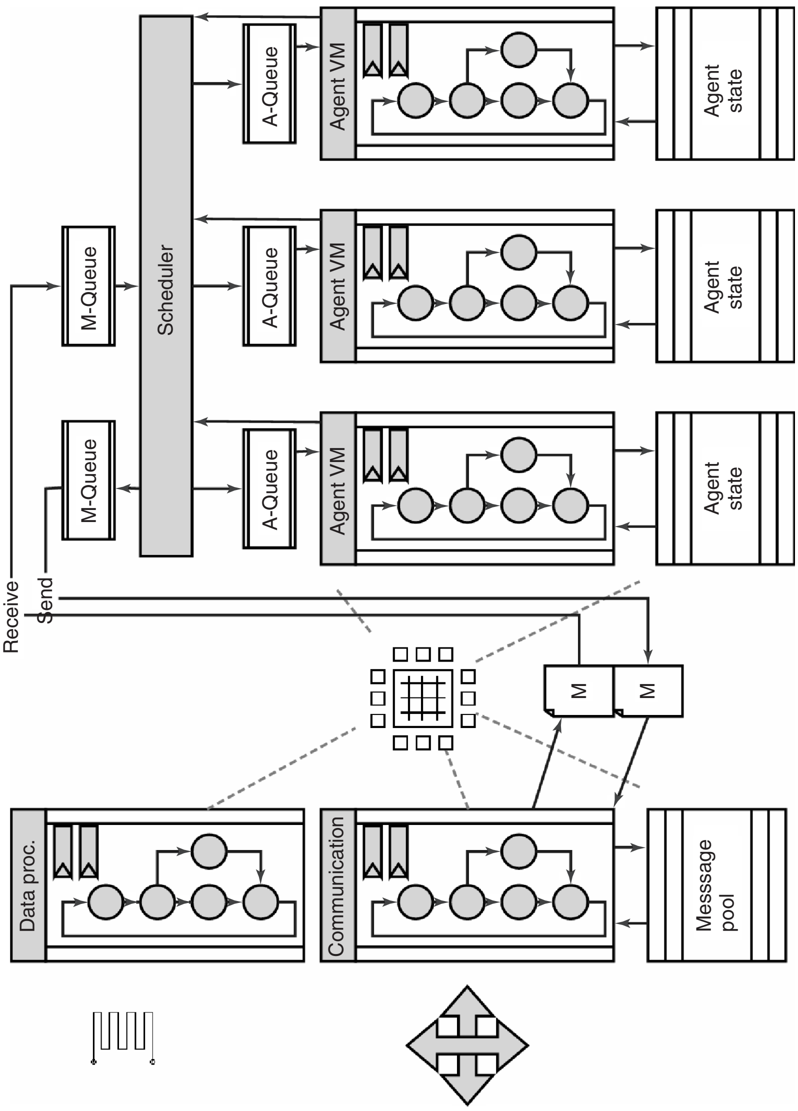



**Figure 17.10** Sensor node building blocks providing mobility and processing of multi-agent systems: parallel agent virtual machines, agent-processing scheduler, communication, and data processing [69].

Multi-agent systems are used to implement

- distributed data processing and information exchange [69];
- data fusion and propagation of information;
- finally lower levels of machine learning methods for fast load inference and classification in a discrete position-force space [29].

An agent approach provides stronger autonomy than a traditional object or remote-procedure-call-based approach. Agents can decide for themselves which actions are performed, and they are capable of reacting on the environment and other agents with flexible behavior.

Traditionally, mobile agents are executed on generic computer architectures [71, 72], which usually cannot easily be reduced to single-chip systems as they are required, for example, in sensorial materials with high sensor node densities.

SoC design embedding low- and high-level data processing in a single microchip ensures a high degree of miniaturization and low-power data-processing systems suitable for local energy-harvesting methods. The runtime environment is modeled on behavioral level using the high-level multi-process programming language ConPro with atomic-guarded actions and inter-process communication (communicating sequential processes) [31], introduced in the previous section.

Internode communication is performed with messages encapsulating agents. Smart message routing provides robustness [30]. The hardware architecture is optimized for mesh networks of data processing nodes, which can be organized, for example, in a 2D grid topology with each node having connections to its up to four direct neighbors.

The functional behavior of agents is implemented with finite-state machines on RTL embedded in the sensor node, shown in Figure 17.10. Only the state of the agent (consisting of control and data state variables) is propagated using messages. For example, the agent state machine implementing the behavior of the smart energy management agent consists of only nine control states and nine data state variables.

### Further Reading

As yet no all-encompassing reference work on sensorial materials exists. However, several aspects of them are covered in the literature on smart structures. Besides, scientific journals have recently accepted and published contributions that delineate the concept. Some of these, such as the work by Lang *et al.* [7], have already been cited above.

Furthermore, the general issue of material-integrated intelligence and sensing as expressed in the term *sensorial materials* is covered as a major aspect in several conference series, of which some examples are named below. As some of the conferences are dynamic in terms of their topics, that is, the list of symposia is put together anew for each time, selected events of the past have been named below.

Naturally, the numerous individual aspects that contribute to realizing sensorial materials, such as NEMS/MEMS technology, energy harvesting and storage, and network data evaluation, are covered by specialized events. These have been omitted here to maintain clarity.

**Books:**

Wadhawan, W.K. (2007) *Smart Structures-Blurring the Distinction between the Living and the Nonliving*, Oxford University Press, Oxford. Gaudenzi, P. (2009) *Smart Structures-Physical Behaviour, Mathematical Modelling and Applications*, John Wiley & Sons, Hoboken.

**Conferences:**

- SysInt Conference Series, International Conference on System Integrated intelligence
  Conference/organizer web site: *www.sysint-conference.org*
  A biannual international event dealing with all aspects of system-integrated intelligence from product development and engineering design to life cycle aspects and covering the physical realization of intelligent structures and materials, as well as the technologies needed for this purpose. Held for the first time in Hanover, Germany, in June 2012 including a special session on sensorial materials, planned for June/July 2014 in Bremen, Germany and June/July 2016 in Paderborn, Germany.
- Smart Systems Integration (SSI)
  Conference/organizer web site: *www.smart-systems-integration.com*
  An annual European conference with accompanying exhibition usually held in Spring at changing locations. The wider topic of smart systems integration regularly includes most aspects of sensorial materials. Organization is supported by the European Technology Platform on Smart Systems Integration (EPoSS).
- E-MRS Spring Meeting
  Conference/organizer web site: *www.emrs-strasbourg.com*
  One of the largest annual European conferences on materials science on a fundamental and applied level, organized by the European Materials Research Society, and with very few exceptions regularly held in Strasbourg in May or June.
  Past years have seen several symposia linked to the topic of sensorial materials, that is:
  – E-MRS Spring Meeting 2010,
    Symposium A: From Embedded Sensors to Sensorial Materials, organized by Professor Walter Lang, Institute for Microsensors, Actuators and Systems, University of Bremen, Germany

  – E-MRS Spring Meeting 2012,
    Symposium Q, organized by Danick Briand, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland.
- Euromat
  Conference/organizer web site: . . . , *www.euromat2009.fems.eu*
  *www.euromat2011.fems.eu*, *www.euromat2013.fems.eu*, . . .
  *www.fems.eu*
  A conference similar in size and diversity to the E-MRS Spring Meeting. Euromat is organized by the Federation of European Materials Societies and held biannually in uneven years in changing countries, with the local materials society hosting the event. As for the E-MRS Spring Meeting, the selection of symposia varies from event to event, with topics linked to sensorial materials regularly covered.
  – Euromat 2011,
    Symposium A53: MEMS/NEMS for Sensorial and Actorial Materials, organized by Dirk Lehmhus, ISIS Sensorial Materials Scientific Centre, University of Bremen, Germany and Professor Jürgen Brugger, École Polytechnique Féderale de Lausanne (EPFL), Lausanne, Switzerland.
- CIMTEC Conference Series
  Conference/organizer web site: *http://www.cimtec-congress.org/*
  A biannual conference usually held in Italy and for the fourth time in 2012. CIMTEC conferences have two recurring topics. One of these is “Smart Materials, Structures and Systems”, the focus in 2012 and thus again in 2016. In 2012, the entire conference held in Montecatini Therme, Italy, from 10 to 14 June, was of relevance for sensorial materials research with a special focus set by symposium G, “Emboding Intelligence in Structures and Integrated Systems.”
- The International Workshop on Structural Health Monitoring
  Conference/organizer web site: *http://structure.stanford.edu/workshop/*
  Rooted in SHM as one of the major fields of application foreseen for sensorial materials, this workshop, which is organized by and held biannually in uneven years at Stanford University, USA, is among the leading international events in the field. It is complemented, in even years, by the “European Workshop on Structural Health Monitoring” (EWSHM) which addresses identical topics.

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