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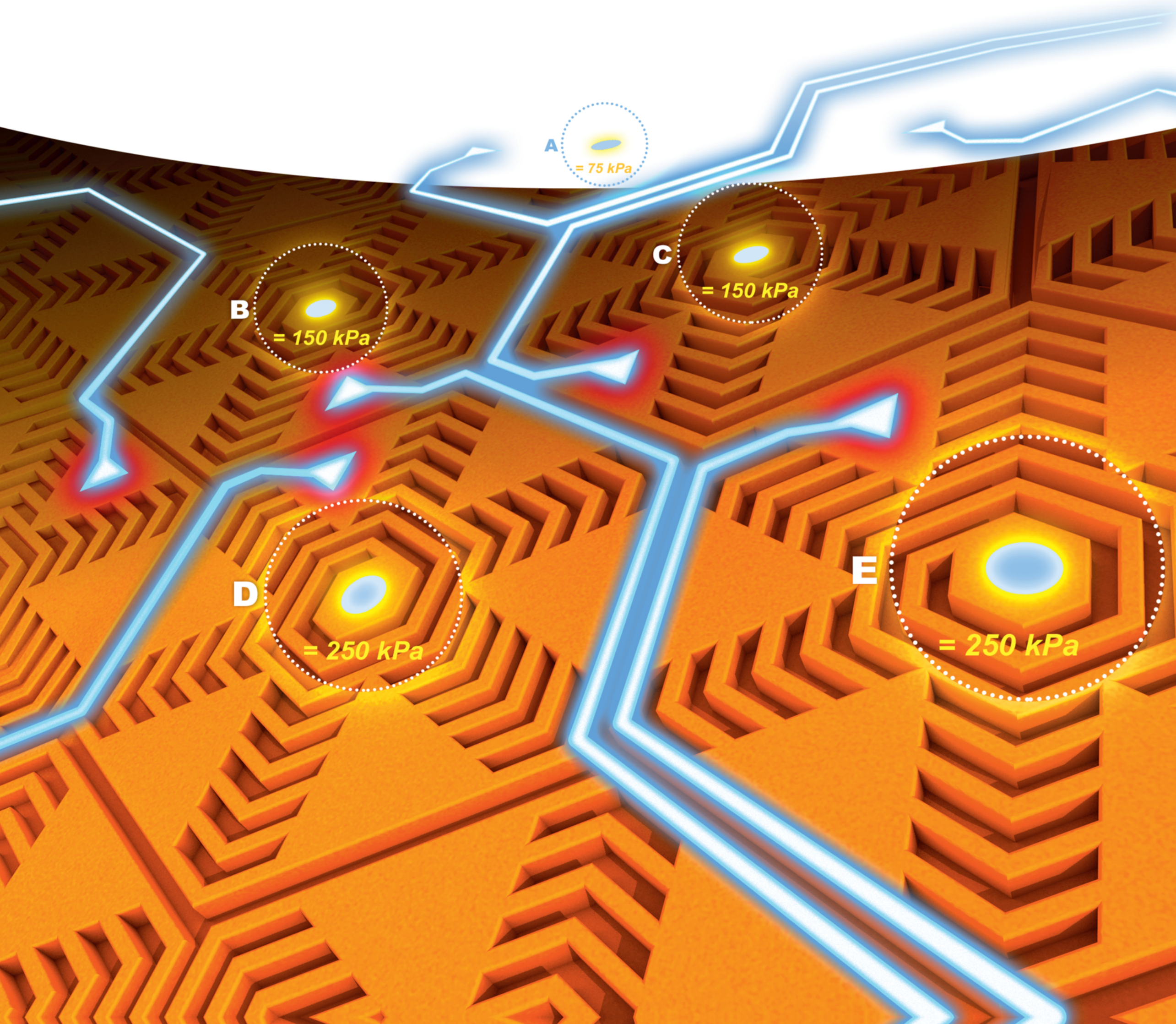

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Foreword

The vision of materials with intelligent behavior has been tantalizing material and computer scientists for many decades. The benefits of such materials, which would more resemble living systems than classical engineered structures, would indeed be tremendous: Materials that can sense and change their properties such as shape, appearance, and other physical properties in response to the environment would allow us to create structures, robots, and other autonomous systems that interact with the environment with animal-like agility and with the robustness common to biological, living systems. In the long run, such materials could even self-assemble and self-heal, and fundamentally change the way how things are made. This vision is particularly nagging as Nature vividly demonstrates these possibilities and their feasibility on a daily basis; yet, progress has been slow and tedious. Unlike conventional engineered structures, Nature tightly integrates sensors, muscles, and nerves with structure. Examples range from our own skin that helps us regulate temperature and provides us with tactile sensing at very high dynamic range to the most complex structure in the known universe, our brains, and more exotic functionality such as camouflage of the cuttlefish or the shape-changing abilities of a bird wing.

In computer science, interest into intelligent material goes back to Toffoli's concept of "Programmable Matter" in the 1990s, and was accelerated by the advent of microelectromechanical structures (MEMSs), which has led to the concept of "smart dust" and the field of sensor networks. At the same time, advances in composite manufacturing have led to the field of "multifunctional materials," and it seems the time has finally come to unite these two fields of which the present book is a first attempt.

Stefan Bosse, Manuel Collet, Dirk Lehmhus, Walter Lang, and Matthias Busse present here one of the first attempts to bridge the currently disparate fields of computer science, robotics, and material engineering. Their diverse backgrounds are reflected in the organization of this book, which follows the same layered approach that has become customary to abstract the inner workings of networked communication from their applications to organize the challenges of material-integrated intelligence in both material science and computing. Establishing this common language and hierarchy is an important first step as it allows the different disciplines to understand where they fit in, the scope of their contribution within the bigger picture, and where the open challenges are.

While this view will be very helpful for the two disparate communities to find common ground, this book does not oversimplify the problem. It remains clear throughout that material-integrated intelligence and structural functionality are indeed at odds. Every additional sensor, communication infrastructure, and computation a computer scientist would wish to integrate into a structure, for example, to perform structural health monitoring, jeopardizes the very structural health of the structure. Similarly, adding the capability for structures to morph, for example, to save fuel during different phases of flight, adds weight to an extent that very likely outweighs the very savings any morphological change could possibly provide. While these constraints seem overly limiting, more pedestrian (in the true sense of the word) applications might not have enough value to justify multifunctional composites.

Yet, natural systems impressively show us that trade-offs in multifunctionality with net benefits are indeed possible and often the only way these systems can survive in a changing environment. It might therefore be worthwhile to put immediate applications aside and indulge in the intellectual challenges of design and distributed computation until emerging applications such as robotics, orthotics, and autonomous systems in general – which will strongly benefit from material-integrated computation – become more mainstream. This book provides the red thread for such a pursuit by providing an overview of recent progress in function scale integration of sensors, power and communication infrastructure, as well as the key computational concepts that such integration could enable, bridging the worlds of the continuous, that is material physics, and the discrete algorithmic world.

Here, one problem becomes very clear: It is not possible to design material-integrated intelligence without understanding both the underlying material physics and the algorithms such intelligence requires. Physics determines the bandwidth, dynamic range, and noise characteristics of sensors and actuators, which define the available inputs and outputs to an algorithm designer. Likewise, certain computational problems require a minimum amount of real estate, energy, and communication bandwidth that the material designer needs to foresee. These challenges are already well understood in robotics, where they are reconciled by a probabilistic view on sensing, actuation, and algorithmic planning. Describing the specific problems that material-integrated intelligence poses will help the community to recognize the similarities between such structures and robotics, and possibly help to leverage insights from probabilistic state estimation, planning, and control that this community has produced in the past decade.

Combining a physical and a computational perspective in a single book will not only help this fledgling field to organize key insights but might also serve as a starting point for a new generation of scientists and engineers who will have their feet comfortably in both the computational and the physical – a prospect that offers tremendous opportunities. For example, it is possible to shift computation into the material and vice versa. The cochlea, which effectively performs a discrete Fourier transform, trades computational with spatial and sensing requirements. Similarly, insect eyes organize their lenses in spatial arrangements that simplify the neural circuitry for rectification of the compound signal, an approach that has become known as "morphological computation." Finally, combinations of active materials can be used to create simple feedback controllers and oscillators. Innovating in this space will require scientists and engineers that are equally at ease with materials and computational concepts.

Another area that is currently untapped in material sciences and builds up on the foundations laid out here is to leverage the principles of self-organization and swarm intelligence to equip future materials, possibly consisting of thousands of pin-head sized computing devices, with intelligence. Receiving interest from both material and computer science, for example, in their study of self-assembly or pattern formation, also known as "Turing Patterns" (after the computer science pioneer Alan Turing who first studied such systems), both communities have not yet connected on creating materials that self-organize – a concept that allows realizing almost limitless functionality.

Back to the here and now, however, the immediate impact research in material-integrated intelligence might have is to provide a new platform for material and computer scientists alike to apply and exchange their tools. Solving the problems of integrating sensors/actuators, computation, communication, and power into smart composites and mass producing them will allow us to create sensor networks and distributed computers of unprecedented scales. Such systems pose the opportunity to perform model predictive control or machine learning *inside* the material, providing unprecedented capabilities and challenges. Likewise, applying the full breadth of what is possible computationally will spur the development of novel sensors and actuators with higher bandwidth, smaller footprints, and lower energy requirements, eventually approximating and transcending natural systems. In order to get there, readers of this book will need to set their disciplinary goggles aside and join us in the quest to make materials computers and computers materials.

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February 10, 2016

Preface

This book addresses a topic that has, to the editors' knowledge, not been covered as comprehensively as this before: material-integrated intelligent systems.

The topic links up with recent, current, and emerging trends like smart system integration, ambient intelligence, or structural electronics. Its background is the understanding that to obtain truly smart objects, it is simply not sufficient to tag them with a sensor node and some associated electronics for data evaluation – nor is it satisfactory to merely embed sensors in materials. Instead, the ultimate goal is to have materials that actually feel in a manner that can be compared with our own capabilities as human beings. The skin, its sensory equipment, and the further processing of data acquired through it is undoubtedly the most referenced model of such a material: Here we find different types of sensors situated in the most suitable places and at high resolution wherever necessary – thousands of them, actually, on your fingertip or on the palm of your hand, capturing pressure together with its first and second derivatives as well as secondary information like temperature or humidity.

Besides the sensors, you have filtering of signals, sensor fusion, and information preprocessing. You have communication of aggregated information to a hierarchy of higher level control systems – your spinal cord, or ultimately your brain, with the information passed finally reaching your consciousness.

The complexity of this system is such that research on its basic principles and capabilities even in humans is an ongoing effort involving researchers from several disciplines like biology, medicine, or neuroscience, to name but a few.

The aim defines the approaches that lead to its technical realization, and technology does not differ from biology here: The topic is highly interdisciplinary irrespective of the world we look at, be it natural or artificial. It requires contributions, in various fields, of materials science, but also of production engineering, microelectronics, microsystems technology, systems engineering, and computer science. In fact, it needs more than contributions, but rather close cooperation. It thus faces all the challenges transgressing the boundaries of scientific disciplines commonly entails–starting from a quite natural lack of fully grasping the capabilities and limitations of neighboring research fields to the simple problem of scientific languages that just do not match and thus impede creating the necessary mutual understanding.

At the same time, the promise linked to solving these difficulties is just about as large as the challenge. Material-integrated intelligent systems encounter an economic environment that moves more and more toward computational capabilities and communication technologies dispersed and networked throughout our daily environment. The concept of smart dust may be seen as earlier formulation of this issue. Currently, it is moving back into focus as a potential facet of the Internet of Things (IoT), today one of the main stimulators of research in material-integrated intelligent systems.

The associated fundamental technological enablers and their interdependence is what we primarily intend to illustrate in this book.

With this vision in mind, we have conceived this book, to which several authors with a broad scientific background have contributed.

Our ambition with it is to help bridge the gaps between the various disciplines they represent by allowing these eminent scientists to present their own views on their area's part in the embracing context.

So whom do we expect to benefit most from this extensive collation of information?

Naturally, the answer to this question determines the form and content of the fundamental chapters of our work.

As primary readers, we have professionals in product development and engineering design in mind who are tasked with the problem of integrating mechanical and electronic systems in a classic mechatronics approach, but on the new level of material integration, which requires additional, new solutions in materials and production processes or data evaluation.

Thus, the perspective of the assumed reader is that of an expert in one of the technological fields involved who needs to gain insight into the adjacent ones to be able to devise and evaluate integrated solutions involving several areas. The background of such a reader can either be academic or industrial. Among the industrial readership, we particularly hope to gain the interest of potential applicants of material-integrated intelligent systems: Our book should provide the necessary pathways and perspectives to help them understand the possibilities the combination of the current technological state of the art from various disciplines can offer.

Besides, we have graduate and postgraduate students in mind who seek an introduction to the field. The character of the book, and the intention to lead professionals to new realms beyond their usual field of practice, is reflected in the attempt to structure and formulate the individual chapters in a way that will allow people with an engineering or natural sciences background to easily follow the discussion even if it is not their particular area of expertise or application that is covered.

For reasons of simplicity and easy access, the book is organized in parts that reflect major research areas. Prior to this, the topic is outlined in an introductory section (Part One) that explains the term material-integrated intelligent systems in more detail, puts it in perspective with past, present, and future scientific and technological trends, and thus provides the motivation for engaging in research and new technology development.

Part Two, System Development, assumes the product development perspective and describes methodologies for designing smart systems on different levels of abstraction.

Part Three, Sensor Technologies, provides fundamental information about different types of sensors and discusses the need for adaptation they face in view of material integration, as well as technological solutions developed toward this end.

Part Four, Material Integration Solutions, swaps perspectives from the electronics and microsystems technology point of view toward mechanical and materials engineering. In this part, we consider the integration problem based on specific material classes (metals, polymers) and the closely associated manufacturing processes.

Part Five, Signal and Data Processing: The Sensor Node Level, describes the fundamentals of this area of expertise and relates them to specific problems of material-integrated systems. The perspective is that of the individual, smart sensor node.

Part Six, Networking and Communication: The Sensor Network Level, extends the scope toward the combination of several such sensor nodes and thus also covers information exchange between them, as well as data evaluation in sensor networks.

Part Seven, Energy Supply, discusses ways of ensuring the availability of sufficient amounts of energy – and levels of power – for a material-integrated system to operate, touching upon aspects like storage of energy and management of resources as well as generation of energy through harvesting or scavenging approaches.

Part Eight, Application Scenarios, either provides examples of realized material-integrated intelligent systems or explains how different areas of application like Structural Health Monitoring or Human–Machine Interaction and/or cooperation could profit from future availability of them.

Common to all parts is a general concept that provides entry points for readers with diverse backgrounds and thus strongly deviating levels of competence in the areas covered. In this sense, we do not see our work as giving definite answers across the width of its scope, but rather as defining and providing the cross-disciplinary interfaces between the various elements that need to be connected to generate what is the topic and the vision of this book – material-integrated intelligent systems.

Putting together this book has required a considerable amount of time and commitment from all the many people involved. We are thus extremely grateful to those researchers who have volunteered to supply a contribution to this work. Essentially, it is their dedication, their effort, their perseverance, and not the least their patience that have made possible the result you, the reader, can hold in your hands today.

We are indebted to Dr. Martin Preuss of Wiley-VCH, who discussed the topic, content, and organization of the book with us at its very beginning and thus helped create the original framework that has now been realized in the form you, as reader, are holding in your hands. For this realization, in turn, we owe gratitude to Nina Stadthaus and Stefanie Volk (Wiley-VCH) who accompanied us throughout the whole process of gathering and organizing primary input as well as secondary information with immeasurable patience, dedication, and a lot of good advice.

Finally, we acknowledge the financial support of the Federal State of Bremen, which facilitated the formation and the initial research work of the ISIS (Integrated Solutions in Sensorial Structure Engineering) Sensorial Materials Scientific Centre at the University of Bremen, without which the achievement this work represents could not have been accomplished.

Stefan Bosse
Dirk Lehmhus
Walter Lang
Matthias Busse

Part One

Introduction

1

On Concepts and Challenges of Realizing Material-Integrated Intelligent Systems

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1.1 Introduction

Material-integrated intelligent systems constitute materials that are able to “feel.” This is the shortest possible definition at hand for the subject of the present book. What it implies will be discussed below, while detailed descriptions of individual aspects and application scenarios will follow in its main parts.

As a concept, material-integrated intelligent systems have implicitly been around for quite some time. To a considerable degree, this is because the concept as such is not so much a human invention, but rather something that is deeply rooted in nature: The human skin and the human nervous system are the typical examples cited pertaining to material-integrated intelligent systems, such as sensorial materials [1–3], robotic materials [4], nervous materials [5], or sensor-array materials [6].

These natural models taken together nicely illustrate the differences between materials with integrated sensor(s) and material-integrated intelligent systems: For one thing, the skin contains a multitude of sensors which do not only capture force or pressure, but also additional aspects like the first and second derivative of pressure or temperature. At the same time, the impression we get when we touch an arbitrary surface is not that of a separate awareness of these factors, but a combined one that is derived from fusion of sensory information.

Besides, we do not base the decisions we make in response to a tactile sensation on quantitative values of pressure, temperature, and so on, and on a deterministic model that links these values to an intended action and its potential outcome. Instead, we rely on experience, that is, on a learned relationship between an action and its outcome in relation to the associated sensory information in one way or another. Translated to technical terms, we thus follow a model-free approach.

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Having said this, we can derive a list of characteristics a material would need for us to concede that it can actually "feel." Such a material must be capable of

- capturing sensory data;
- aggregating data through some local preprocessing, performing data reduction of individual data points;
- further processing this data to derive some higher-level information, gaining knowledge;
- using this knowledge for decision-making, putting it to some internal/local use, or communicating it to higher system levels;
- coping with damage by being dynamic and reconfigurable; and
- achieving a state of awareness of host material and environment, that is, the derivation of a context knowledge.

If the above list represents a functionality-centered perspective, the question that immediately arises is how a technical implementation of this concept could be achieved, and which research domains would need to contribute to it.

On a generic level, material-integrated intelligent systems follow the universal trend in the microelectronics industry, which is typically described as having two orthogonal, primary directions: on the one hand, miniaturization or the "more Moore" development line, and on the other, diversification through the integration of additional, usually analog, functionalities such as sensing, energy supply, and so on – the "more than Moore" approach. In both cases, reference is made to Moore's law, which predicts (from a 1965 point of view) that transistor count in densely packed integrated circuits would double every 2 years, and which has since then approximately been met by actual developments, although with some indications of slowing down since about 2011. Technologically, "more Moore" is usually associated with system on chip (SoC) solutions, whereas "more than Moore" is linked to system in package (SiP) technologies. However, both merge diagonally combining both SoC and SiP approaches to create higher value systems. Clearly, this is the domain into which material-integrated intelligent systems fall. As a consequence, the following research topics need to be addressed in their development:

- miniaturization on component and system level to limit "footprint" within host material;
- system resilience against effects of processing conditions during integration;
- system compliance with host material properties in the embedded state;
- energy supply solutions that support autonomy, like cooperative energy harvesting and storage, and (intelligent) management of resources;
- reliable and robust low power internally and externally directed communication approaches;
- distributed, reliable, and robust low power data evaluation; and
- multiscale design methodologies that span the scope from chip design to smart products and environments.

Mark Weiser, in his landmark 1991 article that predicted many evolutions in computer science we have witnessed since, has set the scene by stating that "in the 21st century, the technology revolution will move into the everyday, the small and the invisible" [7]. Weiser thus anticipated a development that is connected to terms such as ambient intelligence and ubiquitous or pervasive computing.

Material-integrated intelligent systems will both profit from and contribute to the realization of this prediction through their potential of endowing many of the passive materials surrounding us today with perceptive capabilities, and ultimately even adaptive behavior. A large part of the novelty of this approach has its foundations in the notion that miniaturization of systems will allow integration on a level that provides the added functionality without compromising suitability for the primary role to be fulfilled by the material in question. A prominent example in this respect is structural health monitoring (SHM). This application scenario is relevant for safety-critical, load-bearing structures. Safety can be enhanced, or safety factors relaxed, if the exact structural state is known at any moment in time. If material-integrated intelligent systems were selected for this task, a necessary prerequisite would be that the systems themselves do not adversely affect mechanical characteristics of the host material. In other words, the materials designed thus should not afford considering any property degradation caused by the material-integrated systems during the layout of the structure for its primary task. In a further evolution of the concept, the materials themselves could thus be envisaged as semifinished materials in the same way as sheet metal: Their capabilities, including their smartness, would be available as an asset not necessarily targeted at a specific application, but providing for several ones. For production of material-integrated intelligent systems, such a scenario could open up economy of scale effects significantly enhancing their economic viability. At the same time, this would afford production techniques able to cope with the associated large production volume.

It has been suggested that the implementation of material-integrated sensing can either follow a top-down or a bottom-up approach [2]. Focusing specifically on the sensing function, Lang *et al.* [8] propose an even finer distinction, which demarcates a top-down as opposed to a bottom-up approach:

- top-down approach:
  - hybrid integration
  - local additive buildup
- bottom-up approach:
  - generic (intrinsic) sensing properties of materials
  - local growth of sensors using, for example, bioinspired processes

From our current perspective, Lang *et al.*'s proposal excludes the intelligent side of material-integrated intelligent systems and its prerequisites like energy supply by concentrating on the transducer effect and the hardware to implement it. Specifically, the bottom-up approaches still fail to offer solutions that could provide these system components. This is apparent particularly for the generic sensing properties of materials, which remain ineffectual even as sensor until at least some means of detecting (i.e., sensing) the intrinsic effect is added.

The example shows that at least on the level of full intelligent systems, bottom-up approaches do not yet respond satisfactorily to the questions of realization.

An exception, though a theoretical one, is the notion of programmable matter proposed by Toffoli and Margolus. Their original concept assumes spatially distributed computing elements similar to smart sensor nodes capable of nearest neighbor interaction only. Together, they form a material with the inherent capability of information processing. Practically, this concept is reminiscent of physical realizations of cellular or lattice gas automata [9,10].

Later, alternative or extended definitions of programmable matter stress the ability of such materials to alter their physical characteristics in a controlled fashion – controlled either by a user from the outside or autonomously from within the material. In the latter case, the programmable matter makes use of its data evaluation capabilities to respond, for example, to sensor signals. Under this headline, several materials have been understood to represent forms of programmable matter. Material-integrated intelligent systems would fall into this category, too. Since the wider definitions of programmable matter include spatial reconfiguration building on autonomous objects (cells) as building blocks besides information processing, sensing, actuation, and adaptivity, both sensorial materials [1] and robotic materials [4] can be seen as intermediate-level representatives of this overall class of intelligent materials.

Realization of programmable matter thus depends on the scope of properties and the definition adopted. The full spectrum is usually represented by the material being built up of individual, autonomous units of microscopic scale that form the matter itself by docking to each other in different configurations, an ability that requires some relative locomotion, too. "Utility fog" is another designation for a system of microscale autonomous units having such abilities, with the spatial rearrangement not based on the so-called "foglets" as the smart units, but on the flow of the fluid in which they move. Reaching a certain macroscopic shape thus does not have to depend on deliberately moving to a certain location, but can rely on making or refusing connections once the opportunity is there [11]. To date, to the knowledge of the authors, no physical material is available that combines the full set of characteristics envisaged by Toffoli or Hall [10,11].

Obviously, much nearer to implementation is the top-down approach, which essentially coincides with the intermediate, diagonal path in between the pure "more Moore" and the "more than Moore" trend: What the term top-down implies is a hybrid integration approach in which suitable components are adapted to material integration needs and combined to form the required smart sensor network.

First practical developments leading toward sensor nodes combining subsets of the features required by material-integrated intelligent systems – above all, a minute size, a certain level of energy autonomy, and data evaluation as well as communication capabilities – sailed under the "smart dust" flag from the end of the 1990s to the early twenty-first century [12]. Warneke *et al.* concentrated on developing, as they termed it, a "cubic millimeter-sized computer" fully endowed with sensing, energy storage, and data evaluation, plus communication that could create an *ad hoc* network when dispersed, like dust, in a given environment. Clearly, a handful of smart dust sensor nodes embedded in a host material would conform to our own definition of material-integrated intelligent systems and sensorial materials.

Figure 1.1 provides an overview of the main elements of such a system, which mostly form part of the smart dust mote concept, too. The sensorial material as such consists of a material-integrated network of smart sensor nodes that may