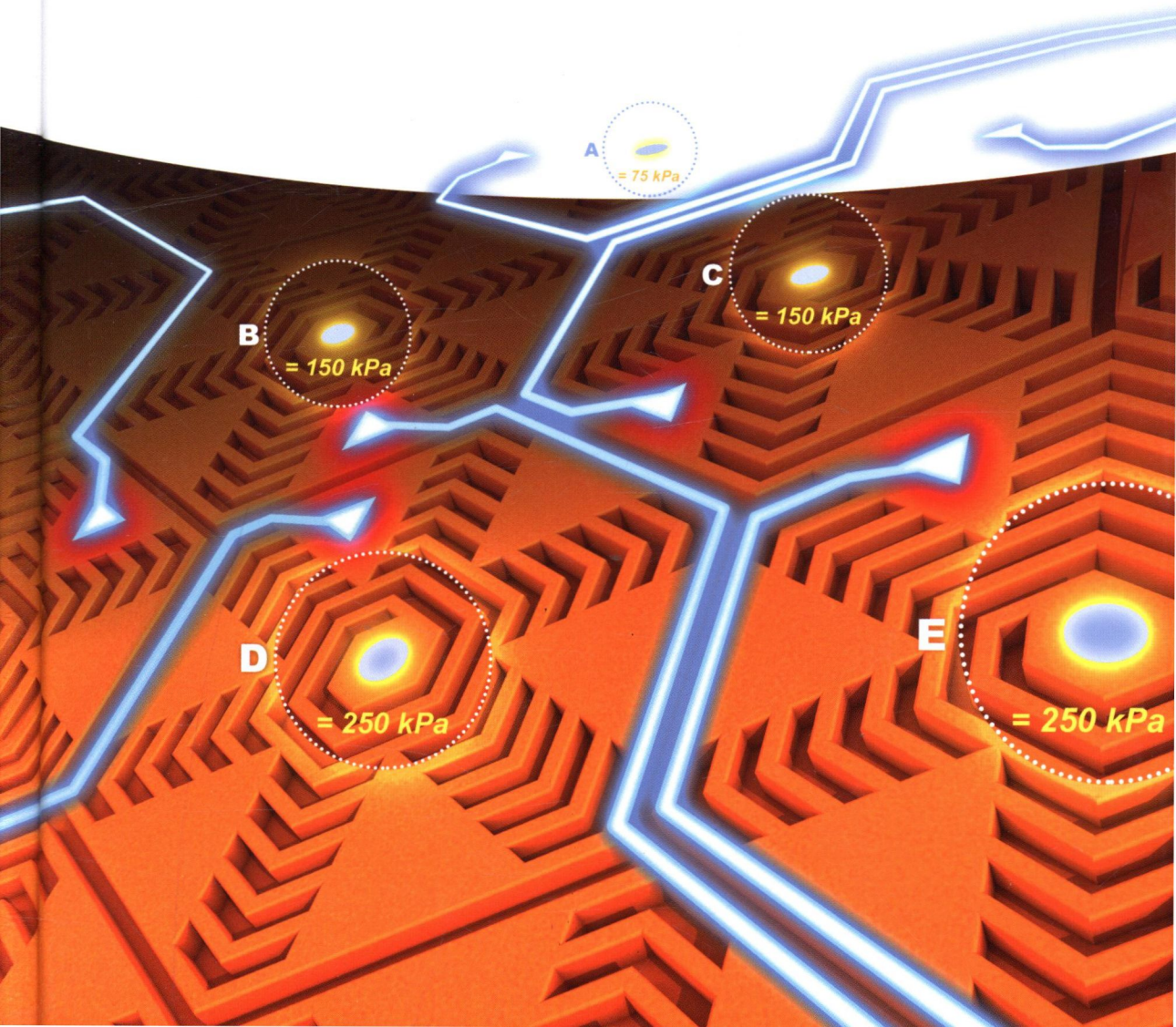


Edited by Stefan Bosse, Dirk Lehmhus,  
Walter Lang, and Matthias Busse

# Material-Integrated Intelligent Systems

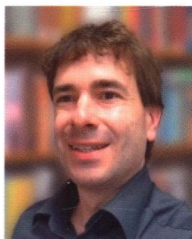
Technology and Applications





Combining different perspectives from materials science, engineering, and computer science, this reference provides a unified view of the various aspects necessary for the successful realization of intelligent systems.

The editors and authors are from academia and research institutions with close ties to industry, and are thus able to offer first-hand information here. They adopt a unique, three-tiered approach such that readers can gain basic, intermediate, and advanced topical knowledge. The technology section of the book is divided into chapters covering the basics of sensor integration in materials, the challenges associated with this approach, data processing, evaluation, and validation, as well as methods for achieving an autonomous energy supply. The applications part then goes on to showcase typical scenarios where material-integrated intelligent systems are already in use, such as for structural health monitoring and smart textiles.



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**Bosse • Lehmnhus  
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**Material-Integrated  
Intelligent Systems**

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Technology and Applications

*Edited by Stefan Bosse, Dirk Lehmhus, Walter Lang, and  
Matthias Busse*

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**Material-Integrated Intelligent Systems**





## 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*



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