An Introduction to Sensorial Materials

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Summary: The concept of Sensorial Materials as an example of materials with integrated sensory and intelligent capabilities is explained. Its relation to similar notions like Adaptive Metacomposites or Smart Dust is outlined and contrasted to the idea of self-X materials, with self-healing variants as their best known exponents. Top-down and bottom-up approaches to achieving such capabilities are briefly touched, and the present concentration of many efforts on the former is justified. Major challenges that follow from this choice are sketched and matched with the contributions to the present conference's special session on enabling technologies for Sensorial Materials, for which this document supplies the introductory words.

Keywords: Sensorial Materials, Material-Integrated Intelligence, Self-Healing Materials, Sensor Integration, Function Scale Integration.

"In 20 years from now, we will have structure that talks to us: Tells us how it's feeling, where it hurts, how it changed its shape, and what loads it's experiencing." This vision was formulated more than ten years ago by W. J. Renton of the Boeing Company [1]. It is still a vision, and if we talk to aerospace industry representatives today, we hear that 20 years may still be a realistic estimate despite the time that passed since Renton's remark.

Nevertheless, the aim remains the same. As has been the case so often, we are motivated by the apparent success of a natural example to strive towards it: We have learned from the study of cancellous bone about ways to adapt technical structures to the loads for which we design them – at minimum weight. The crux lies in the term "for which we design them". Recurring to the bone model, we see that nature faces a similar challenge. The internal structural change we witness in bones is mainly controlled by lasting loads, while sudden, unexpected as well as lower-level cyclic ones, that might still do damage, cannot be accounted for. In engineering design, the advent of virtual testing and the resulting possibility of studying growing numbers of load cases may alleviate the problem, but by definition, the unforeseen is not included in design specifications.

So what is nature's response? Basically, it is the ability to feel, realized in the case of the bone in the periosteum, which contains nociceptive nerve endings. Translated to technical terms, these are the mechanical sensors that allow us to feel pain - pain that initiates, typically as a reflex on a lower level of consciousness, the motion that may save our skin and bone. So when do we make use of this ability? For countering the unexpected, as a secondary measure for covering the breach that is left ajar by the primary source of structural stability we rely on, the basic strength and adaptability of our skeletal system.

By adding this secondary approach to engineering materials and structures, we may counterbalance at least in part our restriction to a limited number of design loads. There will be further benefits, of course: We may save weight, and cost for maintenance, to name but a few. But besides, what this measure implies is a shift of paradigms in engineering design: Whereas before, we have dimensioned components to averaged loads which we knew to be relevant for a complete series of parts, we are now starting to individualize these parts: We endow them with the added capability of coping with loads that are unique for each individual component. We move from a general, statistically justified to a single-part-and-service-life perspective, and it turns out we cannot do so on a broader scale by means of a control approach lacking feedback loops. We have to implement some traces of autonomy, and thus of situational awareness.

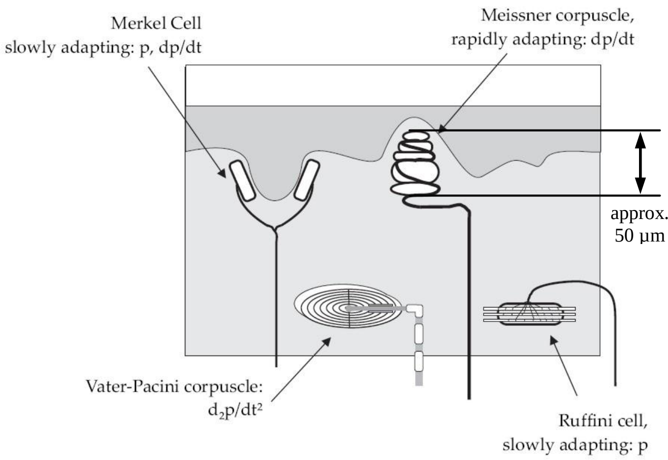

Figure 1. Sources of sensitivity in the human skin – image adapted from Lang et al. giving information about approximate size of the Meissner corpuscle: The same order of magnitude can be achieved in pressure sensors produced via micro system technology today, but clearly, this alone does not generate what we call feeling [2,3].

So we need to teach our materials some feeling. But what does it mean to "feel"? If we take a look at the human skin, we see a veritable zoo of sensitive elements, from slowly adapting Merkel cells, which record pressure and its first derivative, to rapidly responding Meissner corpuscles that again detect the first derivative of pressure, to deeper-embedded Vater-Pacini corpuscles that concentrate on its second derivative, side by side with slowly adapting Ruffini cells, which dedicate their attentiveness once more to pressure itself (Fig. 1) [2,3]. Apparently, what we call feeling is a result of sensor fusion using all this varied input.

Considering this observation, we must conclude that providing the materials we envisage with sensors alone will not do the trick. We need more, and this more includes local data processing, networking of sensor nodes and communication facilities - these features given, further aspects like energy supply come in naturally. This is exactly what our vision is about: We define Sensorial Materials as materials that gather data about their environment and/or their own state, process these data locally and make use of the information derived internally or communicate it to the outside world. Essentially, if we compare this concept to the mere application of sensors to an otherwise conventional structure, what we need to do is move the functional range from outside and beside to inside the structure or rather material (Fig. 2). Stressing the material in this context has special significance, since the notion of a Sensorial Material implies its use as a semi-finished product. As such, it can be formed to match the requirements of a specific application – formed physically, that is, to attain a certain geometry, but also with respect to its mental furnishings. These can include context- and thus application-dependent rules for data evaluation or internal system models that may depend on final geometry and processing history and evolve if the structural state changes. At the final point of this development, not a structure or a component shall be made to feel, but it shall inherit this ability from its constituent materials. Based on emergence phenomena, the result might then turn out to be more than the sum of all parts.

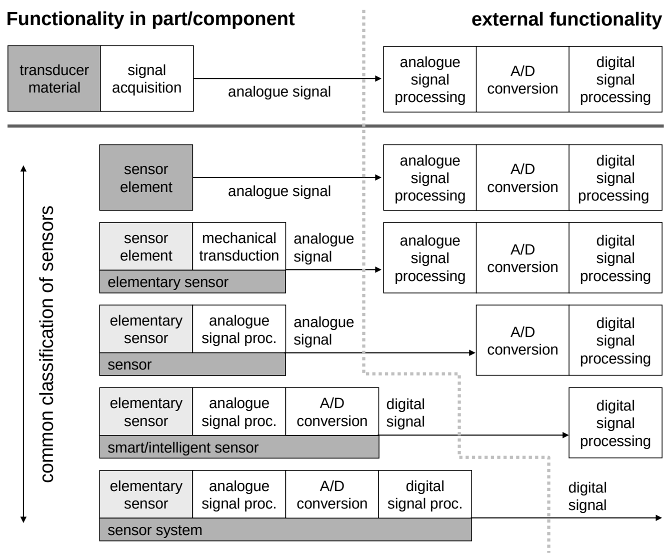

Figure 2. Realising a Sensorial Material means moving functionality from sensing to data processing and network/external communication from the external world and out of dedicated, usually centralized supplementary devices (right hand side) into the material itself (left hand side) – representation adapted from [4], networking of sensor systems and communication beyond the boundaries of the material as further levels of complexity not depicted here.

A critical mind could wonder now why we put so much stress on sensing, apparently neglecting actuation. Again we turn to nature for an explanation. Studying the human body, we find that collection of sensorial input and facilitation of movement are realized on entirely different length scales. Correctly interpreting a situation that requires a reaction needs considerable amounts of data and thus finely dispersed and complementary sensor nodes. In contrast, a suitable response will in the great majority of cases be possible on the basis of a limited number of joints, associated degrees of freedom and actuators, i.e. muscles.

It is obvious that other concepts, such as the Adaptive Metacomposites suggested by Manuel Collet [5] or aspects of Smart Dust adhere to our definition of Sensorial Materials. With respect to the latter, the individual smart sensor nodes or motes suggested by Warneke et al. [6], equipped with various sensing capabilities and together forming a wireless network clearly just lack embedding in a host material to constitute a Sensorial Material. Self-X materials, on the other hand, of which self-healing variants are archetypal and currently the most developed, fall into yet another category. Their response to critical loads is complex, too, but typically defined and constrained by their micro structural build-up, which reflects known failure modes, and was deliberately selected for this purpose in their initial development. Thus their reflexes are hard-wired and lack the flexibility and context sensitivity which can in principle be implemented in Sensorial Materials.

Having thus defined Sensorial Materials, the question remains how to realise them. Currently, four different approaches are foreseen [2]:

- hybrid integration
- local build-up via additive manufacturing
- use of generic/intrinsic sensorial properties of the host material
- generic growth, e.g. via self-assembly techniques, of sensor structures

Of these fundamental methods, the first is clearly top-down, while the last is bottom-up. The others can effectively contribute to either solution, with an emphasis on the former. However, though research is done along the latter lines, too, for example at the Max Planck Institute for Intelligent Systems in Stuttgart and Tübingen, currently top-down hybrid integration must seem the preferred choice for realising first generations of Sensorial Materials and their likes. Major research issues associated with it include, among others,

- miniaturization of components, including approaches like function scale integration [2],
- compliant sensors and microelectronics that can stand material integration and service life alike,
- real-time data evaluation and system identification,
- low power solutions for sensing, signal/data processing and communication
- reliable energy supply on the microscale, covering energy harvesting, storage and management, as well as
- fundamental principles and tools for design and dimensioning of intelligent materials and material systems to safety, reliability and robustness targets.

The challenges that remain in these fields are numerous. However, the motivation to address them has been put down before, and the reward that tackling them promises can clearly justify further investment in research – the more so since the principles and methods linked to the wider field of Sensorial Materials, are of an enabling nature [2,7]. As Mark Weiser stated as early as 1991, “in the 21st century, the technology revolution will move into the everyday, the small and the invisible” [8]. What is predicted here has been labelled ambient intelligence and pervasive or ubiquitous computing and implies further notions like the idea of an Internet of Things. Among its technological backbones is the realization and wide-spread distribution of cyber-physical systems – and thus of the likes of the Sensorial Materials discussed here, because ubiquitous computing will absolutely require ubiquitous sensing to stay in touch with the environment it shall serve and exploit in terms of linking computational resources and information. How such an intelligent environment can be organized is another primary research issue in the wider field of Sensorial Materials. Its tremendous potential for new applications and services is out of any doubt.

The present symposium, which is introduced by this text, addresses several of the above issues. A conceptual overview, using vibroacoustic control as application scenario, is provided by Manuel Collet of Femto-ST, Besançon, France [6]. Advanced integration techniques are presented by Fraunhofer IFAM (C. Pille) and Fraunhofer IST (S. Biehl) as well as IMSAS of the University of Bremen (A. Ibragimov): The focus is on integration of sensors and microsystems in metal castings. Polymer matrices, in contrast, are processed at the Technical University of Chemnitz, and here specifically at the Institute for Lightweight Structures (M. Heinrich) in cooperation with the Center for Microtechnologies (R. Schulze), Fraunhofer IAP (M. Wegener) and Fraunhofer ENAS (M. Schüller). Functionalization of material surfaces is executed by Laser Zentrum Hanover using laser thin film patterning (J. Duesing). To the same end, Volker Zöllmer of Fraunhofer IFAM introduces Functional Printing as an additive or direct-write technique, looking particularly at nanoparticle inks that form a basis of the underlying processes. Also concerned with surfaces is Frank Jakobs, again of IMSAS, who provides them with haptic sensing based on a new concept involving microfluidic techniques. Advanced optical sensors that use derivatives of the well-known fibre Bragg grating (FBG) sensor principle to detect bending besides longitudinal strain are discussed by Simon Kibben of BIAS. Christoph Budelmann of DFKI employs optical fibres as joint energy and information transfer path in sensor networks. Energy management in such networks is treated by Thomas Behrmann of BIMAQ, University of Bremen, with a focus on rapid control prototyping as a tool for the layout of energy-aware sensor networks. In contrast, Stefan Bosse of the University of Bremen’s working group on Robotics suggests Artificial Intelligence (AI)-inspired methods for data evaluation and communication in sensor networks. Here, too, special attention is paid to realizing low power systems.

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