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Material-Integrated Intelligent Systems: A Review on State of the Art, Challenges and Trends

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Abstract: As a concept, material-integrated intelligent systems represent the vision of embedding not only sensors, but full sensor networks in technical materials, irrespective of their application being dominated by functional or structural properties. In this sense, the term full sensor networks encompasses the sensors, the associated signal processing, the data evaluation and information retrieval, provisions for communication within the network and beyond it, and an energy supply system. The concept as such can be applied to any type or class of host material, ranging from organic materials to composites, metals and ceramics. The result are materials that are, in a manner of speaking, able to "feel" in the broader sense associated with this term. The present work discusses current approaches towards realizing material-integrated intelligent systems on hard- and software level as well as potential applications for such materials. It names the specific challenges associated with integration and suggests state of the art and future paths to address them. A special section is dedicated to the advent of additive manufacturing techniques adapted to facilitate sensor integration: The present growth in this field is expected to also extend into the realm of sensor-integrated materials and structures.

Keywords: sensors; smart structures; sensor integration; intelligent materials; sensor networks; sensorial materials; multi-agent systems; inverse FEM; additive manufacturing

1. Introduction

The term “material-integrated intelligent system” describes what can be seen as an evolution of the concept of smart structures: In fact, the latter could be based on the former. If an engineering structure becomes smart through an addition of sensor and associated data evaluation systems, in some cases also added actuators, then material integration implies that this addition is not an external application, but an embedding of the system providing smartness within the materials that make up this structure [1]. Several designations have been coined for such systems – besides the descriptive one used in the present paper’s headline, sensorial materials [2, 3], robotic materials [4] and nervous materials [5, 6] have become part of the technical terminology. What connects them all is the notion that these materials should not just sense but rather feel – in other words, they would need signal and data processing and evaluation implemented in the material, faculties that in turn demand, for their support and interaction, energy supply, communication links etc. Needless to say, this requires some complexity and establishes new research needs. Which these might be, and how the issues that have thus arisen might be solved will be discussed briefly in the following chapters – mostly on a general level, except for the example of additive manufacturing (AM): This technique, which builds components layer-by-layer in hitherto unknown complexity and without making use of moulds or tools, is currently receiving considerable, though well-deserved attention: AM has the potential to change some paradigms in production technology and organization [7]. Thus it is only natural that in our present context, we direct part of our attention to these technology potential for sensor integration, the more so since practical work is already being done in this area. Following the initial, technologically oriented discussion, we briefly present some application scenarios which would profit from material-integrated sensing solutions.

2. Requirements and Challenges

Seen from a life cycle perspective, material integration requires first, in the Beginning of Life or BoL phase, that the sensor systems embedded in an arbitrary material survive the very process of integration. In the middle of life (MoL) phase, they need to perform, reproducibly and reliably, over their full planned lifetime, which is controlled by the lifetime of the product they form part of. Finally, though this is an aspect not discussed here, for lack of space, there must be a solution for what to do once the End of Life (EoL) has been reached: Recycling is a critical issue here, since we are necessarily talking about heterogeneous systems that are not easily separated. The present text however will focus on the BoL and EoL.

Looking at these phases, the main challenges for material-integrated systems are defined by the basic requirements they ought to meet [1, 8]:

- No degradation operational fitness and capabilities of embedded systems.
- No adverse effects on mechanical/functional properties of host material or structure.
- Reliability of data acquisition, processing, and information mining even under conditions of partial component and/or network node failure.
- Reliability and long-term stability of the entire system.

- Highest levels of autonomy, including energy supply, and "low to no" maintenance needs.
- Competitive economics, for various series sizes including high volume production.
- Realization of a benefit, technological or economic, for the host system.

According to this list, reliability in its many facets turns out to be of primary importance for material-integrated intelligent systems. In view of the limited accessibility of material-integrated systems, this is not surprising. Not listed above, but for many applications of equal importance, is flexibility: A system meant to detect critical states, and react to them, and act throughout their prevalence, may have to be a system that is able to reflect its own change of state. Imagine a structural health monitoring system: Should it not be able to maintain its functionality even after damage has been experienced? Not surprisingly, what is easily formulated here is significantly more difficult to implement.

3. Hardware-level Adaption for Integration

3.1. The Scalability Issue of Data Processing

Traditionally, hardware and software are separated. The computer architecture is designed first, and afterwards the software is created assigning an application to the data processing system. This approach has the disadvantage of a mismatch between hardware and software. The hardware must be designed generically and must operate program-controlled, preventing a resource and performance optimization. Newer trends in hardware-software co-design relax this issue, but are commonly still applied to large scale systems.

Integration of data processing systems in materials requires a shift from traditional multi-component processing systems with single high computational power and high storage capacity to single component and microchip scaled low-resource embedded systems (System-on-Chip designs). These single-component designs, however, tend to suffer from a reduction in computational power and data storage. In consequence, a paradigm shift is required towards distributed networked computing to compensate these limitations and allow handling of multiple algorithms used in structural monitoring or perceptive applications. The scaling of algorithms, communication, and data processing down to microchip level is one of the major issues in computer science, breaking large units into smaller pieces under hard resource and robustness constraints, covered by the new scientific area "Material Informatics", discussed in Section 4.

3.2. Withstanding the Embedding Process

Most production processes, be they primary or secondary shaping, subject the material that are to form a technical component to significant mechanical and thermal loads: In casting, the material is molten to give it its shape – in forging, this is not the case, but then again, this implies that higher mechanical loads are necessary. High pressure die casting of light alloys like aluminum combines mechanical loads of roughly up to 200 MPa with temperatures that are typically above 700°C – still, the thermal loads on embedded components can be controlled in this process because heat extraction rates are higher, and thus the time of exposure to the most severe conditions is limited. Still, either high temperature material solutions for functional components or thermal decoupling is necessary. Typically, the first approach is chosen for sensors, which typically need to be in intimate contact with the host material, while the second is reserved for any electronic component to be embedded in a light metal casting [9-11]. Less critical in terms of processing conditions are typically polymer-based processes – both temperatures and pressures are much reduced here when compared to the processing of metals.

But even under less critical conditions, and once part production is survived, service loads have to be sustained: Locally, these may be increased by mismatches in thermal (coefficient of thermal expansion) and mechanical properties (Young's modulus) of the embedded system and host material, as several authors have pointed out [12, 13]. To compensate mechanical loads originating from such misadjustment, stretchable and flexible electronics are being researched [14]. Figure 3.2.-1 provides an overview of major approaches followed.

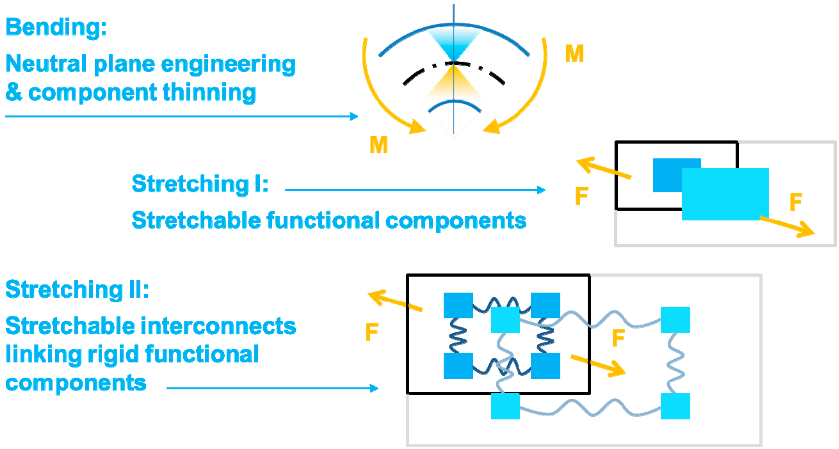
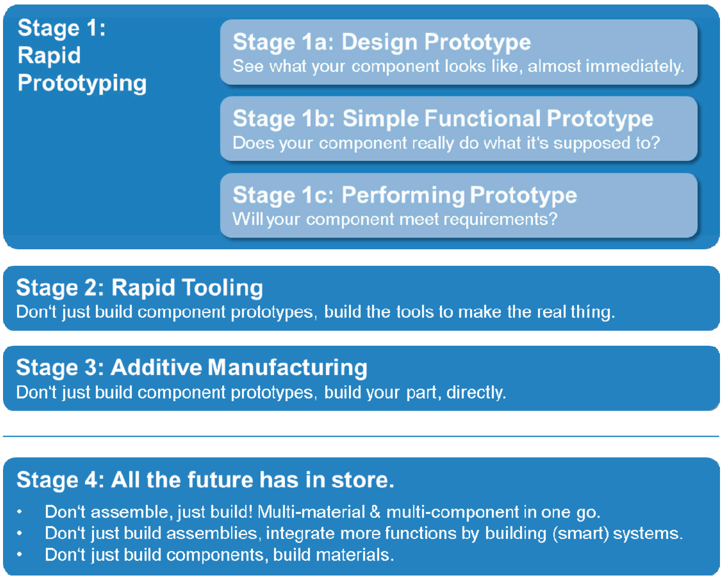


Figure 3.2.-1. Overview of fundamental strategies adopted to achieve flexibility and/or stretchability of sensors and electronic components as summarized by [7].

These issues solved, the problem of the footprint of the embedded structure remains – if an embedded sensor or system can be seen as a potential weakness in the host material, its size should be reduced as much as possible. This can either be done by continued miniaturization along the path delineated by Moore's law, or by the reduction of system volume to the level that is absolutely mandatory to maintain functionality, e.g. by removal, as a final step in production, of material that facilitates processing only. For the latter approach, Lang *et al.* have coined the term "Function Scale Integration" – a main strategy employed is getting rid of substrates that provide rigidity and thus ease handling of MEMS components but are irrelevant for the final application [14]. An interesting practical solution in this respect has been demonstrated for fibre-reinforced composites with embedded "smart patches" based on piezoelectric actuators: Here, the substrate material has been selected to match the thermoplastic matrix of the fibre-reinforced composite acting as host material – thus during part shaping and consolidation, which coincides with the integration of the patch, through melting of substrate and matrix, the interface between both just disappears [15].

3.3. *Special Topic: Sensor Integration in Additive Manufacturing*

According to .ASTM international committee F42, additive manufacturing (AM) is the process "of joining materials to make objects from 3D model data, usually layer up on layer, as opposed to subtractive manufacturing methodologies, such as traditional machining" [16]. Because AM produces parts directly from digital models without the need for moulds or tools, the term direct digital manufacturing has also been used to describe these methods on a more general level [17]. A review covering the diversity of the available methods has recently been published by Gao *et al.* [7].Origins and perspectives of the technology are briefly outlined in Figure 3.3.-1 below.



Stage 1: Rapid Prototyping

Stage 1a: Design Prototype
See what your component looks like, almost immediately.

Stage 1b: Simple Functional Prototype
Does your component really do what it's supposed to?

Stage 1c: Performing Prototype
Will your component meet requirements?

Stage 2: Rapid Tooling
Don't just build component prototypes, build the tools to make the real thing.

Stage 3: Additive Manufacturing
Don't just build component prototypes, build your part, directly.

Stage 4: All the future has in store.

- Don't assemble, just build! Multi-material & multi-component in one go.
- Don't just build assemblies, integrate more functions by building (smart) systems.
- Don't just build components, build materials.

Figure 3.3.-1. A simplified history of AM and an outlook towards the future.

Presently, due to its general capabilities and major technological advances, AM techniques are subject to significant interest. Needless to say, the notion that "material can be placed almost anywhere in a controlled manner" directly leads to the question of whether it might not be possible to put "almost any material anywhere", thus implying spatially defined material transitions, which could facilitate e.g. the direct build-up of components with integrated electronics, sensor, or, in a first step, at least conductive paths. In fact, most of the processes available today do not live up to this vision yet, but nevertheless several studies on sensor-integrated AM parts on somewhat lower levels of complexity, or using more complex machinery, exist.

Looking towards the farther future, since in principle it allows in-process switching of the materials deposited, the so-called LENS^{TM} process [18], may prove to be most promising for the direct build-up of complex, multi-material functional structures: Belonging to the subclass of directed energy deposition processes, this method is based on a constant feed of the building material in particulate form to the spot where it should be added, fusing it to the previously deposited material by means of some energy source – a laser in the case of the LENS^{TM} process. The alternative are process combinations: Lopes *et al.* and Espalin *et al.* have recently reported about a hybrid manufacturing system which combines processes like fused deposition modelling (FDM, an AM process belonging to the material extrusion subclass) with pick-and-place operations to integrate electronic components as well as micro machining, micro dispensing, printing and thermal embedding of Cu wires to create interconnects between these [19, 20].

4. Software-Level Adaptation for Integration: Materials Informatics

As already outlined in Section 3, hardware and software is much more closely coupled than in traditional data processing systems. The shift from centralized multi-component coarse-grained to fine-grained distributed computing systems consisting of single components (microchips) creates new issues related to synchronization, message routing, stability, and topological organization. Distributed computing extends the ontology and complexity of sensing systems significantly. Goal-orientated computing can replace traditional service-orientated system [21]. Resource allocation and usage can be a further challenge.

Mobile agents can deal with this extended "system world" and the distributed resource allocation by introducing autonomous behaviour and planning, adaptive behaviour based on environmental changes (and changes of the ontology), goal-oriented group behaviour in multi-agent systems, and self-organization.

It has be shown that agent processing and processing platforms can be scaled down to microchip level [22] without the requirement of an operating system or standard computer environment, enabling the integration of material-integrated sensing systems with advanced computing capabilities and the connection to computer networks and the Internet [23] with a unified computing approach. Furthermore, mobile agents are self-contained processing units that are only loosely coupled (in terms of programming interfaces) to specific platforms and network nodes. This feature enables the arbitrary and heterogeneous composition of nodes in a sensor networks, not constrained by specific topologies, architectures, and technologies (e.g., well suited for the Smart Dust approach [24]).

Real-time processing, *i.e.*, computation under time constraints, can be a prerequisite for reactive monitoring systems used, e.g., in structural monitoring applications. Self-organization, unconstrained mobility, and autonomous behaviour of agents can complicate the implementation of real-time systems, especially concerning hard real-time systems that fail on time bound violation. Distributed real-time systems are generally hard to designed, not only limited to multi-agent systems.

The distribution of algorithms is a similar issue known from parallelization, but much more difficult due to the communication costs arising in loosely coupled systems (compared with shared memory). Furthermore, distribution of computation in material-integrated systems must treat the failure of some partial computations as the normal case, and not as an exception as in parallel strongly coupled systems. It is well known that matrix computation or filtering, e.g., Sobel edge filters, can be well distributed by decomposing in row and column operations shifted in the network [1].

5. Application Scenarios for Material-Integrated Intelligent Systems

The main application scenarios for material-integrated intelligence are characterized by a need for multiple interconnected sensors extended over an extended area or volume. Concrete examples include

- fly-by-feel applications, e. g. for autonomous flight and UAVs [25],
- load, structural health and condition monitoring, in cases linked to advanced maintenance capabilities like Maintenance on Demand (MoD), predictive/preactive maintenance [26, 27],
- artificial/smart/electronic skin for robotics and/or prostheses [28],
- tangible user interfaces etc., including next generation automotive user interfaces [29]

The Smart Skin scenario is of specific interest because its objective is tactile sensing, which has sometimes been used in the past to explain the notion of material-integrated intelligent systems more graphically [14]. Valle *et al.* have recently provided a review of this topic specifically focusing on the integration of intelligence, *i.e.* local data processing facilities, highlighting the role of machine learning techniques in evaluation of tactile data by means of pattern recognition approaches [30].

6. Conclusions/Outlook

In this work, we have shown that material-integrated intelligent systems bear considerable promise for applications in which engineering structures profit from awareness on their state, and from sensor-based links to their environment which are accessible to immediate evaluation and interpretation. We have also shown that several challenges still need to be addressed in this context before such intelligent materials will become commonplace. Among these is the necessary adaptation of embedded systems to the harsh conditions of material processing, but also to the loads, thermal or mechanical, they will be subjected to in service. Besides these hardware-related issues, we have looked at the software side, which in fact may even help to address the above issues by providing the embedded sensor systems with an algorithm-based capability to sustain and even overcome partial failure, establishing a new aspect within the area of Materials Informatics, finally merging hardware and software.

Besides these general points, we have highlighted the potential of AM techniques for producing material-integrated intelligent systems, concluding that certain process classes, specifically the directed energy deposition subgroup, which is based on material feed rather than local consolidation of a liquid or powder bed and thus facilitates in-process switching of materials, are more suited for achieving this aim than others: Presently, however, intelligent system production case studies tend to rely on combination of several processes, part of which may be AM ones.

Author Contributions

Both authors contributed equally to this work. Focus of Dirk Lehmhus contribution was more on the hardware, materials and processes level, while Stefan Bosse concentrated on hardware issues in as far as electronics were concerned, and on software-related matters and specifically artificial intelligence (AI) techniques in data evaluation.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Bosse, S.; Lechleiter, A.: Structural Health and Load Monitoring with Material-embedded Sensor Networks and Self-organizing Multi-Agent Systems. Procedia Technology 15 (2014) 668-690.
2. Lang, W.; Lehmhus, D.; van der Zwaag, S.; Dorey, R.: Sensorial Materials – A vision about where progress in sensor integration may lead to. Sensors and Actuators A: Physical 171 (2011) 1-2.
3. Lehmhus, D.; Bosse, S.; Busse, M.: Sensorial Materials. In: Lehmhus, D.; Busse, M.; Herrmann, A.S.; Kayvantash, K. [Eds.]: Structural Materials and Processes in Transportation. Wiley-VCH, Weinh. 2013.
4. McEvoy, M. A.; Correll, N.: Materials that combine sensing, actuation, computation and communication. Science 347 (2015) 1261689-1 to -8.
5. Mekid, S.; Kwon, O. J.: Nervous Materials: A New Approach for better Contriol, Reliability and Safety of Structures. Science of Advanced Materials 1 (2009) 276-285.
6. Mekid, S.; Saheb, N.; Khan, S. M. A.; Qureshi, K. K.: Towards sensor array materials: Can failure be delayed? Science and Technology of Advanced Materials 16 (2015) 034607 (15pp).
7. Gao, W.; Zhanga, Y.; Ramanujan, D.; Ramani, K.; Chen, Y.; Williams, C. B.; Wang, C. C. L.; Shin, Y. C.; Zhang, S.;Zavattieri, P. D.: The Status, Challenges, and Future of Additive Manufacturing in Engineering. Computer-Aided Design 69 (2015) 65–89.
8. Lehmhus, D.: Material-integrated Intelligent Systems – Notes on State of the Art and Current Trends. Proceedings of the 5th Scientific Symposium of the CRC/TR PT-PIESA, Dresden, Germany, September 14th-16th, 2015.
9. Pille, C. In-process embedding of piezo sensors and RFID transponders into cast parts for autonomous manufacturing logistics. Proceedings of the Smart Systems Integration (SSI) 2010, Como (Italy), March 23rd-24th, 2010.
10. Ibragimov, A.; Pleteit, H.; Pille, C.; Lang, W. A Thermoelectric Energy Harvester Directly Embedded Into Casted Aluminum. IEEE Electron Device Letters 33 (2012) 233-235.
11. Klassen, A.; Rübner, M.; Ilg, J.; Rupitsch, S. J.; Lerch, R.; Singer, R. F.; Körner, C. Influence of the fabrication process on the functionality of piezoceramic patch transducers embedded in aluminum die castings. Smart Materials and Structures 21 (2012) 115014 (11p).
12. Dumstorff, G.; Paul, S.; Lang, W.: Integration without disruption: The basic challenge of sensor integration. IEEE Sensors Journal 14 (2014) 2102-2111.
13. Lecavelliers des Etangs-Lavellois, A. et al.: A converging route towards very high frequency, mechanically flexible, and performance stable integrated electronics. J. of Applied Physics 113 (2013) ID 153701.
14. Lang., W.; Jakobs, F.; Tolstosheeva, E.; Sturm, H.; Ibragimov, A.; Kesel, A.; Lehmhus, D.; Dicke, U.: From Embedded Sensors to Sensorial Materials – the road to function scale integration. Sensors and Actuators A: Physical 171 (2011) 3-11.
15. Hufenbach, W.; Gude, M.; Heber, T.: Development of novel piezoceramic modules for adaptive thermoplastic composite structures capable for series production. Sens. Act. A156 (2009) 20-27.

16. Active Standard ASTM F2792 Standard Terminology for Additive Manufacturing Technologies.ASTM International, West Conshohocken, PA, USA, 2012.
17. Chen, D.; Heyer, S.; Ibbotson, S.; Salonitis, K.; Steingrímssonb, J. G.; Thiede, S.: Direct digital manufacturing: definition, evolution, and sustainability implications. Journal of Cleaner Production107 (2015) 615–625.
18. Atwood, C.; Griffith, M; Harwell, L; Schlinger, E; Ensz, M; Smugeresky, J; Romero, J. A; Greene, D; Reckaway, D Laser Engineered Net Shaping (LENS^{TM}): A Tool for Direct Fabrication of Metal Parts. In: ICALEO '98. Int. Congr. Appl. Lasers Electro-Opt., Orlando, FL, 1998, 801.
19. Lopes, J. A.; MacDonald, E.; Wicker, R. B. Integrating stereolithography and direct print technologies for 3D structural electronics fabrication.Rapid Prototyp. J. 18 (2012) 129–143.
20. Espalin, D.; Muse, D.W.; MacDonald, E.; Wicker, R. B.: 3D Printing multifunctionality: structures with electronics. International Journal of Advanced Manufacturing Technology 72 (2014) 963-978.
21. Palanca, J.; Navarro, M.; Julian, V.; and García-Fornes, A., "Distributed goal-oriented computing," Journal of Systems and Software, vol. 85, no. 7, pp. 1540–1557, Feb. 2012.
22. Bosse, S..: Distributed Agent-based Computing in Material-Embedded Sensor Network Systems with the Agent-on-Chip Architecture (Article), IEEE Sensors Journal, Special Issue MIS, 2014, DOI:10.1109/JSEN.2014.2301938..
23. Bosse, S.: Unified Distributed Computing and Co-ordination in Pervasive/Ubiquitous Networks with Mobile Multi-Agent Systems using a Modular and Portable Agent Code Processing Platform. Proc. Comp. Science 40 (2015), doi:10.1016/j.procs.2015.08.312.
24. Warneke, B.; Last, M.; Liebowitz, B.; Pister, K. S. J.: Smart Dust: Communicating with a Cubic-Millimeter Computer. Computer 34 (2001) 44-51.
25. Salowitz, N.; Chang, F.-K.: Bio-inspired intelligent sensing materials for fly-by-feel autonomous vehicles. IEEE Explore, 2012, doi: 10.1109/ICSENS.2012.6411534.
26. Stajano, F. et al.: Smart bridges, smart tunnels: Transforming wireless sensor networks from research prototypes into robust engineering infrastructure. Ad Hoc Networks 8 (2010) 872-888.
27. Diamanti, K.; Soutis, C.: Structural health monitoring techniques for aircraft composite structures. Progress in Aerospace Science 46 (2010) 342-352.
28. Dahiya, R. S. et al.: Directions toward effective utilization of tactile skin: A Review. IEEE Sensors J. 13 (2013) 4121-4138.
29. Celentano, A.; Dubois, E.: Metaphors, analogies, symbols: in search of naturalness in tangible user interfaces. Proc. Computer Science 39 (2014) 99-106.
30. Seminara, L.; Pinna, L.; Ibrahim, A.; Noli, L.; Caviglia, S.; Gastaldo, P.; Valle, M.: Towards integrating intelligence in electronic skin. Mechatronics (2015), DOI:10.1016/j.mechatronics.2015.04.001.