Smart sensor systems – Aspects of low-power devices, energy harvesting, and artificial intelligence

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Abstract: Monitoring of buildings and engineering structures in general, and of adaptive waterside structures in particular, requires smart sensor systems. The temporal as well as environmental constraints associated with long-term monitoring and harsh conditions impose exceptional requirements on the sensor systems. Aspects of low power consumption, long-term stability of sensing devices, autonomous operation by robust energy harvesting concepts and dependable data acquisition for a real-time description of the system behavior by artificial intelligence are key elements for the implementation of smart sensor systems, enabling energy-efficient monitoring and control of adaptive waterside structures. This article addresses the challenges and prospects of novel concepts for the realization of smart sensor systems.

1 Introduction and Challenges

The devastating flood disaster in 2021 has once again clearly revealed the consequences of climate change, such as flooding and other extreme weather events, in particular for waterside structures. Significantly more information acquired at a much earlier stage are required for a safe and sustainable operation of these structures because predictive maintenance measures are all the more successful the earlier they are taken. Particular challenges to be considered are that these structures are used to be unique specimens of enormous size having a considerably longer service life as compared to other technical facilities. Their rate of change due to deterioration is very low and thus hardly measurable. The concept of “digital twins” known from cyber-physical systems has the potential to diagnose and predict the structural behavior based on physical sensory data.

To answer the central question of mechanically adaptive structures of buildings, methods for the long-term monitoring of local overstresses on the sensory side and a methodology for the subsequent control on the actuator side are inseparable. As “long-term” typically means several
decades up to a century, autonomous dependable operation of the system is indispensable. Powering the devices as well as their long-term stability are key issues. The basic engineering challenges on the sensory side with focus on long-term monitoring are the development of (i) sensory methods for detecting overstresses including corrosion and degradation without external electrical energy supply (zero-power sensing), (ii) methods for reading out and evaluating the information stored in the zero-power device and for resetting the device, (iii) an alarm mechanism to inform users in case of emergency. Redundancy and data fusion on the system level of digital twins will ensure consistent data acquisition. For autonomous powering, energy harvesting methods are required. Considering that energy storage also will degrade over that long period by charging and discharging, an absolute strict energy management with minimal power consuming devices is inevitable. Even with the progress in ultra-low-power electronics, autonomous operation over several decades or a century is not yet possible. Hence, strategies for passive sensing without active energy supply have to be addressed. The harvested energy will be used only for the absolutely required tasks of on-demand sensor readouts and data transmissions as well as for alarming users in case of emergencies.

Among the various approaches for energy harvesting, a microbial fuel cell technology for the energy-autonomous operation of sensors and actuators at sea or on structures at shore is appealing to ensure long-term energy supply of such systems for decades. Microbial fuel cells are powered by bacteria that catalyze a direct conversion of chemical energy into electrical energy.

2 State of the art

In recent years, waterside structures, such as bridges, dams, wharves, and port facilities, have been particularly exposed to natural hazards caused by climate change (Wakeman et al., 2015). Because riparian structures represent a group of critical infrastructure, several structural health monitoring (SHM) research approaches have focused on protecting riparian structures (Rizzo, 2012). In addition, advances in computer science, particularly in artificial intelligence and data management, as well as the increasing use of wireless technologies, have stimulated discussion of SHM of critical infrastructure (including near-water structures) into a new perspective. In modern wireless SHM systems sensor nodes are equipped with a high degree of “intelligence,” which allows the embedding of sophisticated algorithms and models to analyze structural behavior (Lynch, 2006). In addition, modern concepts of data management, which enable developing digital representations of physical systems – as “digital twins” (Booyse et al., 2020) – for the early detection of defects in manufacturing, can be advantageously adapted to SHM, which in turn supports the implementation of predictive maintenance measures. These concepts need to be dovetailed and adapted to the specifics of water-related structures. However, active devices for sensing, actuating, and computing as well as wireless data transmission require energy. The trade-off between power supply and long-term operation needs to be solved.

Current progress enables numerous mobile applications, with electronic systems becoming more and more powerful on the one hand, and as low-power systems they consume less and less energy on the other. Even though microelectronics is advancing and components require less electrical power for their operation, autonomous energy supply over several decades is an unsolved problem. Batteries in the form of electrochemical cells discharge themselves over the
years without active use. Accumulators also have finite charging cycles and cannot bridge such
time scales. In measurement technology, we are used to measurement data being recorded and
available at a more or less constant sampling rate. For this, the sensors must also be continu-
ously supplied with energy. For some years, efforts have been undertaken to develop passive
sensors that record and store limit load states without an external electrical energy supply. One
example is a sensor for detecting a deflection with an implemented analog AD converter
(Schmitt et al., 2020). The approach of passive sensor technology now needs to be further de-
veloped using smart materials that change their properties under the influence of environmental
parameters and suitable geometries in such a way that a zero-power sensor that can be pro-
grammed to record and store multiple events to be read out and reset when required under ex-
ternal electrical power supply.

In electrical engineering, intensive research is being conducte d on energy harvesting methods
for this purpose, in order to generate electrical energy from the environment by converting light,
kinetic energy, from electromagnetic fields or temperature gradients (Cao et al., 2017). For
long-term applications, it is of utmost relevance that the harvester works reliably and requires
no maintenance. In this regard, it is advantageous that the system operates independently of
light conditions, contains no moving parts, and requires no additional infrastructure such as
transmission towers. The approach of microbial fuel cells with, in principle, achievable energy
densities of several tens of mW/m² is suitable for use in and near water (Schrader et al., 2016).
Microbial fuel cells for the realization of energy-autonomous systems have existed for several
years. Professor Ieropoulos' group at University of Southampton has developed systems that
can even power autonomous robotic systems (Philamore et al., 2016). Such systems show amaz-
ing robustness. Many systems run stably for hundreds of days (Cristiani et al., 2019). This char-
acteristic is also believed to have led the U.S. Navy to research these systems in order to develop
energy-autonomous sensor systems (Tender, 2014). Overall, a large number of implemented
systems already exist that measure parameters such as dissolved oxygen concentration or heavy
metal concentration (Shantaram and others, 2005). Systems are becoming more powerful, so
that wireless provision of measurement data is available (Walter et al., 2020). Despite this pro-
gress, generic reactor designs for use in open water are lacking. In contrast to applications in
sediment, where sufficient organic material is available to the microorganisms at the anode
under anoxic conditions, for use in free water aspects of organic material supply need to be
addressed as well as up-conversion the low voltages from the harvester for practical use and
temporary storage of the energy. Due to the envisaged service life of several decades, conven-
tionally rechargeable batteries are also reaching their limits. Concepts with super-capacitors
have to be investigated and implemented.

3 Prospective approaches

To address the challenges of SHM over several decades with the unsolved problems discussed
above, novel concepts for realizing smart sensor systems have to be investigated. Decentralized
self-adaptive digital twins for waterside structures with zero-power sensing for long-term mon-
itoring of local overstresses, and microbiological reactors for powering the micro devices are
discussed in the following.
Figure 1 shows the concept of decentralized self-adaptive digital twins for waterside structures where sensor nodes detect the response of the structure to environmental impacts and external devices as underwater robots (µAUV) provide additional environmental information, such as underwater flows. All the data are collected and processed in a decentralized self-adaptive digital twin. Decentralization and self-adaptability enable a stand-alone operation of the SHM system without the need for long-range communication with a central server. With a digital twin the structural behavior can be modelled, diagnosed, and slow minor changes as used for long-term monitoring can be predicted.

Lessons learned from the past help to consequently hybridize the decentralized physical models by coupling the models with classical data-based models and transfer them to waterside structures as decentralized, self-adaptive digital twins. The physics-based models are coupled with data-based models and implemented as full-fledged digital twins by transferring the physical principles into the digital domain and equipping digital twins with monitoring and control systems. Given the mismatch between physical models and the inherently resource-limited wireless SHM systems (particularly in terms of degrees of freedom to be measured), techniques to reduce the model order for coupling digital twins with structure monitoring systems have to be considered. Finally, for self-adaptation, a multi-agent system approach accompanied by machine learning techniques is used. The decentralization of the digital twins is the focus of interest, i.e., the resource-efficient embedding in wireless monitoring and control systems. The physics-based models of the digital twins are decomposed into partial models, with each partial model embedded in a single wireless sensor node. The overall model composed of the partial models will be validated against the digital model. In addition, the self-adaptive digital twins can be extended to a smart city in and on the water. As a result, focus on methods for integrating the self-adaptive digital twins into IoT frameworks directs future developments with multisensory data fusion allowing data (or information and knowledge) from heterogeneous, external sources to be integrated to improve the predictive capabilities of the digital twins.
Essential aspects for the development of the digital twin are extraction of information (and knowledge) from SHM data, enabling the structure monitoring systems to perform autonomous self-diagnostics, and the implementation of intelligent structure control mechanisms via actuators. Further aspects focus on the development of multi-agent system approaches to induce collective (swarm) intelligence in wireless sensor networks and to detect structural anomalies on demand using autonomously migrating software entities (Smarsly and H. Law, 2013). Other research in embedded modeling for wireless structural monitoring systems addresses fault diagnostics in distributed sensor systems (Dragos and Smarsly, 2016) and system identification (Dragos, et al., 2018). Artificial intelligence (AI) methods for sensor systems, particularly coupled with traditional methods for pattern recognition and classical structural mechanics, are used to improve the resilience of engineering structures (Law et al., 2014). For this purpose, fully autonomous structural monitoring systems and intelligent structures were implemented, mathematically abstracted in a generally applicable manner, and finally formalized via an engineering-understandable descriptive calculus (Gürlebeck et al., 2019; Theiler and Smarsly, 2018).

The information source for the digital twin are sensors. For long-term operation, sensors have to consume minimal power, ideally zero. This novel concept of zero-power sensor technology has to be considered both on a system level and on a device level. As constant sampling rate will unnecessarily consume power, even no relevant information is available, a new strategy is addressed using smart passive transducers with analog storage of the measured variable. Active readout requiring power is performed only on demand or when set critical limits are exceeded. The approach introduced above reduces the power consumption to an absolute minimum. One of the most power consuming task is the wireless data transmission, hence this should be restricted in operation. Since the system does not continuously send data to users, an alarm mechanism must be implemented to inform the user in case of an emergency. The algorithms of the digital twin also have to be adopted to manage limited data sampling. On device level, passive sensors with integration of smart materials that change their properties under the influence of environmental parameters and appropriate design geometries are used to implement zero-power sensors that can be programmed to record and store multiple events to be read out and reset when required under external electrical power supply.

For the design and fabrication of the zero-power devices, novel 3D patterning and fabrication techniques, such as selected laser-induced etching (SLE) or 2 photon polymerization (2PP) provide an increase in the degree of freedom for the design and integration of polymer-based and non-polymer-based materials. Smart material integration is well known in microsystems technology (Akay et al., 2017; Schlicke et al., 2020). Combination of 2PP and silicon technology has already been successfully demonstrated (Bohne et al., 2019). Complex 3D devices as a spinal cord implant fabricated by SLE have been recently achieved (Rennpferdt et al., 2021; von Poblotzki et al., 2019).

Sensors for the detection of overstress (strain, acceleration, temperature) and corrosion as well as degradation are required. Due to the focus on long-term applications, even with the concept of passive zero-power sensors, a robust energy harvesting schema is inevitable for the on demand readout as well as for the emergency operation. Figure 2 shows the principle of a microbial fuel cell, which can be used in applications at shore.
Microorganisms have developed a special form of respiration, in which electrons can be delivered to insoluble electron acceptors on the cell surface. In this process, the cytochromes show little substrate specificity, but allow the catalysis of electron transfer to electron accepting surfaces, limited only by the redox potential of the electron acceptor. The electron-transfer mechanisms have been developed during evolution for respiration with iron and manganese oxides. In application, an electrode can be offered to organisms as a surrogate of these metal oxides. Since the process is enzyme-catalyzed, the electrodes can be made from simple graphite materials. The organisms also gain the necessary energy to grow through the process. Therefore, the biocatalyst continuously renews itself and strives to improve through adaptation as part of evolution making this approach being robust for long-term application.

Microbial fuel cells have already been developed for many applications in sediment. However, for general use in free water the technology needs to be extended to include free-floating microbial fuel cells where the small amount of organic carbon in seawater can produce enough energy to power the sensor system. Nature shows that even small amounts of organic carbon in seawater are sufficient to provide food for a large number of organisms by means of filtration. The size spectrum of filter-feeding organisms ranges from sessile organisms such as sponges/corals to large free-living animals such as whale sharks/baleen whales. This principle of nature could be used to develop microbial fuel cells. The tidal current is expected to carry the water through filtering areas that mimic baleen. The filtered material shall accumulate in the anode compartment of the microbial fuel cell where it shall be oxidized.

Key elements for the development of this free-floating microbial fuel cells are applied bioelectrochemistry (Bursac et al., 2017; Gescher et al., 2014; Edel et al., 2019; Gescher et al., 2013; Simonte et al., 2017) and the expertise for isolation of biocatalysts for organic carbon source elimination.
4 Summary and conclusions

Damage and deterioration of waterside structures, affecting structural reliability and safety, typically occur as results of ageing, mechanical impacts, and harsh environmental conditions, the latter increasingly observed as one of the consequences of climate change, such as heavy downpours, floods, storms, or heat waves. To assess damage and deterioration at early stages, monitoring strategies are devised. With recent advancements in information and communication technologies, the monitoring strategies are implemented through smart sensor systems. The harsh environmental conditions as well as the time-variant behavior of adaptive waterside structures, which require coupling monitoring strategies with appropriate control strategies, place exceptional demands on the smart sensor systems. This article, upon analyzing the state of the art, has addressed the challenges and prospects of novel concepts to realize smart sensor systems for adaptive waterside structures. Emphasis has been placed on low-power devices, energy harvesting, and artificial intelligence. It has been concluded that low power consumption, long-term stability of sensors, autonomous operation through robust energy harvesting concepts, and reliable data acquisition for real-time description of system behavior through artificial intelligence are key elements for implementing smart sensor systems enabling energy-efficient monitoring and control of adaptive waterside structures. Last, but not least, it has been illuminated that, to solve the open problems associated with smart sensor systems for adaptive waterside structures, multi-disciplinary collaborations are required between various disciplines, such as civil engineering, electrical engineering, bio-engineering, and computer sciences.

References


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