



Life-cycle zero-power sensing in structural health monitoring: A conceptualization

Joud N. Satme ^a, Han Liu ^b, Pranav Agrawal ^c, Austin R.J. Downey ^{a,d,*},
Simon Laflamme ^b, Sriram Narasimhan ^c

^a Department of Mechanical Engineering, University of South Carolina, 300 Main Street, Columbia, 29201, SC, USA

^b Department of Civil, Construction and Environmental Engineering, Iowa State University, 813 Bissell Road, Ames, 50011, Iowa, USA

^c Department of Civil and Environmental Engineering, University of California Los Angeles, 5731 Boelter Hall, Los Angeles, 90095, CA, USA

^d Department of Civil and Environmental Engineering, University of South Carolina, 300 Main Street, Columbia, 29201, SC, USA

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ABSTRACT

This work presents a novel framework for evaluating life-cycle zero-power sensors for structural health monitoring (SHM). The framework is built on five critical evaluation metrics identified as most significant to life-cycle zero-power sensing: measurement, memory reset ability, power efficiency, data transfer, and material integrability. These metrics are applied systematically to nine representative sensor technologies drawn from fields such as MEMS, optomechanics, soft robotics, and passive RFID. Each metric is assessed using a scoring approach that distinguishes between cases where studies provide clear and measurable specifications (considered more relevant), general statements (considered relevant), or no explicit information (considered not relevant). This enables an objective and structured comparison of sensor technologies, capturing both qualitative descriptions and quantitative specifications. The main achievements of this work are twofold: (1) the introduction of a unified scalar-based methodology for quantifying life-cycle zero-power capability based on the five identified metrics; and (2) the classification of existing sensor technologies within this framework using the scoring approach, establishing a basis for benchmarking and guiding the design of future life-cycle zero-power SHM sensors.

1. Introduction

Structural health monitoring (SHM) is the automation of the condition assessment process of an engineered system [1]. The design of an SHM system includes the selection of appropriate sensors, data acquisition systems, and signal processing algorithms. Information obtained from SHM is subsequently used to inform operators or decision support systems to take timely maintenance actions, optimize resource allocation, and ensure the safety and longevity of the structure. SHM systems may be used temporarily or installed for long-term applications. For either time scale, the aim is to provide useful, actionable information to the system's operators through the continuous and reliable monitoring of critical parameters such as load [2], stress [3], strain [4], shock [5], vibration [6], temperature [7], humidity and moisture content [8] over the lifespan of a structure, termed *life-cycle sensing*.

Structural life-cycle is defined as the duration in which a structure remains operational without requiring major repairs or retrofits that significantly alter its system dynamics, such as the introduction of additional supports or the replacement of original structural segments.

From a design point of view, the expected life of a structure may be 50 years based on the ASCE's 2021 Infrastructure Technical Report [9], however, structures routinely serve their original function past 50 years. When seeking to expand the structural life-cycle beyond the design life of 50 years, continuous monitoring could play a key role in maintaining the usability of the structure. SHM over an entire life-cycle means that the structure is monitored not just during its peak use phase, but from the beginning to the end of its existence. This comprehensive approach allows for early detection of problems and a better understanding of how the structure ages and deteriorates over time [10]. While research into advanced materials is actively being pursued to combat deterioration and extend service life [11], such as the development of optimized mix designs where partial replacement of microsilica with natural pozzolan achieved corrosion performance comparable to conventional concretes, sensing technologies remain essential to provide continuous feedback on structural performance. It follows that sensor selection for an SHM system to be deployed over such a duration is a complex task that involves the evaluation of many

* Correspondence to: 300 Main Street, Columbia, 29201, SC, USA.
E-mail address: austindowney@sc.edu (A.R.J. Downey).

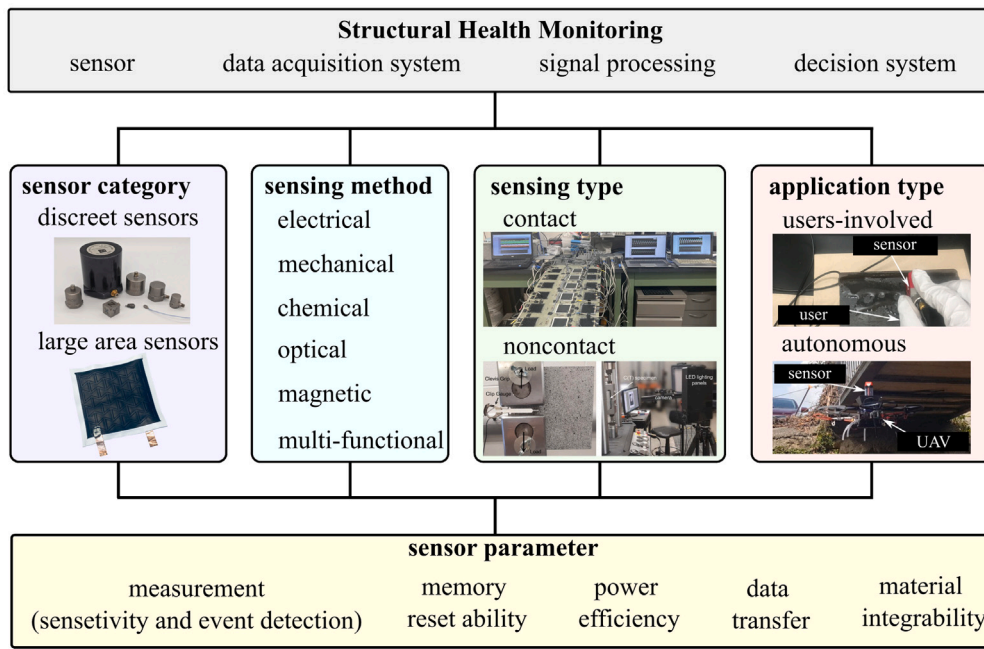


Fig. 1. Overview of sensor evaluation for the structural health monitoring process.

parameters and their influence on overall sensing system robustness and efficiency [12].

Fig. 1 diagrams a simplified overview of the key considerations in sensor selection. Current measurement technologies may not survive through the life-cycle of a structure due to possible issues associated with mechanical deterioration from exposure to the environment or software obsolescence. In particular, environmental factors such as temperature fluctuations, humidity, chemical exposure, and ultraviolet (UV) radiation can degrade sensor materials and components, leading to a loss of accuracy or complete sensor failure over time [13]. Additionally, sensors installed in high-stress areas, such as bridge decks or steel girders, can experience fatigue-related damage, compromising their functionality as the structure experiences repeated load cycles over the years [14].

Integrating sensors into complex monitoring systems introduces challenges related to data management and software upkeep, where older sensors could become incompatible with modern data acquisition systems as software systems evolve, leading to software obsolescence. This can occur through updates in communication protocols, changes in system architecture, or loss of manufacturer support [15]. Recent work has systematically reviewed the application of Bayesian Networks (BN) in SHM, detailing their use in probabilistic damage identification, hierarchical multi-sensor data fusion, uncertainty quantification, and risk-informed maintenance planning [16]. Of particular relevance are Dynamic Bayesian Network (DBN) formulations, which enable time-evolving state estimation and probabilistic updating as new monitoring data become available, providing a structured framework for modeling measurement noise, environmental variability, and incomplete data. As sensor networks become more interconnected and data-heavy, managing cybersecurity risks, firmware updates, and evolving communication standards further complicates long-term sensor functionality [17]. Recent work has also highlighted the vulnerability of long-term SHM data streams to extreme environmental events, where non-stationary and nonlinear structural responses can degrade predictive accuracy and lead to missing or corrupted data [18]. Probabilistic, uncertainty-aware modeling frameworks have been proposed to address these challenges, underscoring that life-cycle sensing must account not only for hardware durability but also for long-term data reliability under severe operating conditions.

Energy consumption remains a persistent issue that many SHM sensors rely on continuous or periodic power supply to function, necessitating either wired connections, which are vulnerable to physical damage, or batteries that need frequent replacement [19]. The energy efficiency challenge is compounded by the remote and sometimes inaccessible locations of many structural components, making sensor maintenance costly and logistically difficult. Low-power wireless sensor networks and energy harvesting techniques have been proposed as potential solutions, but these technologies are still maturing and may not yet offer a viable life-cycle solution [20]. Recent reviews have highlighted the growing application of chipless, passive, and UHF RFID technologies for wireless crack monitoring in both concrete and metal structures [21]. These systems offer low-cost and battery-free operation; however, limitations such as short transmission distance, environmental sensitivity, and frequency-dependent performance remain challenges for full life-cycle deployment.

Current literature proposes best practices for ensuring robustness, reliability, and longevity of sensing systems [22]. However, best practices applied to current sensing technologies may not achieve the overarching goal of life-cycle sensing. This is mainly because many of these systems experience issues such as power inefficiency, sensor degradation, and incompatibility with evolving infrastructures over time. Long-term material integrability in SHM is governed primarily by the resilience of the sensor–structure interface under sustained environmental exposure and cyclic loading, where degradation mechanisms progressively alter load transfer, signal fidelity, and ultimately the reliability of structural state inference. In bonded sensing architectures, environmental exposure can preferentially weaken the interface even when the structure’s material response remains comparatively stable. For example, humid aging of single-lap adhesive joints immersed in water at elevated temperature led to rapid changes in joint deformability and fracture behavior; combined experimental–numerical results indicated that, after aging, the interface becomes the dominant weakened region, with findings that “the interface has been mostly impacted and weakened by water”, and that it becomes the most favorable location for crack propagation after aging [23]. This evidence is directly relevant to SHM sensor mounting strategies (adhesive bonding, encapsulation layers, grouts), because it shows that durability limits may be dictated by interface chemistry and transport-driven degradation (e.g., moisture ingress, swelling gradients, hydrolysis) rather

than bulk constituent strength alone [23]. Interface degradation is also shown to have measurable, frequency-dependent effects on transduction performance in permanently bonded piezoelectric systems. A systematic study of partially debonded PZT actuators demonstrated that the electromechanical coupling varies with debonding across a wide frequency range, producing both amplitude and phase changes, including signal delay and amplitude reduction that scale with debond size, shape, and location [24]. Quantitatively, the reported results include delays on the order of 18% for partial debonding cases and amplitude reductions that can reach 62% (reported for a large debonding fraction), with sensitivity to actuation frequency relative to the PZT resonance [24]. In practice, this means that long-term bond deterioration can introduce systematic bias and non-stationarity into guided-wave or impedance-based SHM features, even in the absence of structural damage. Critically, several studies show that interface degradation can be misinterpreted as structural damage unless explicit sensor-fault discrimination is included. In impedance-based SHM using a piezoelectric smart interface, the bonding layer is identified as a key pathway that controls shear transfer from the PZT to the interface, and defects in this layer change the measured electromechanical impedance in ways that could be “falsely interpreted” as damage unless self-diagnostic features are used [25]. The same work develops diagnostic logic and an impedance formulation that explicitly introduces parameters for shear-lag, debonding, breakage, and structural damage, enabling separation of sensor/interface faults from true integrity changes [25]. Taken together with the debonding-induced amplitude/phase changes observed under ultrasonic excitation [24], these results indicate that interface-state observability (e.g., monitoring resonant features or impedance signatures tied to bonding condition) is a necessary component of actionable, long-duration SHM deployments. Beyond interface physics, long-term integrability also requires system-level strategies for drift and degradation detection to preserve data trustworthiness. A review of sensor degradation impacts highlights that degradation introduces systematic measurement errors, worsens error metrics (e.g., MSE/RMSE), and reduces correlation between sensor output and the true physical state, which propagates into prognostics and maintenance decisions (e.g., biasing remaining useful life estimation or condition-based maintenance triggers) [26]. Complementary to this, work on redundant sensor architectures shows that when multiple sensors are used in a one-out-of-two configuration, the discrepancy signal evolves over time due to degradation processes, motivating trend detection and prediction methods that forecast when discrepancy will reach a shutdown threshold and allow maintenance scheduling before fail-safe activation [27]. For life-cycle SHM, these findings motivate a combined approach: (i) treat the sensor–structure interface as a degradable component with its own state and failure modes [23–25]; and (ii) embed diagnostics/prognostics mechanisms (self-diagnosis features, redundancy, discrepancy trending) to detect when interface or sensor degradation, not structural damage, is driving apparent feature changes [25–27]. From an engineering standpoint, these results support actionable integration guidance: protective approaches (coatings/encapsulation) must be evaluated not only for sensor survivability but for their long-term effect on interfacial transport and adhesion under humidity/temperature cycling [23]; bonding designs should anticipate that partial debonding can introduce frequency-dependent distortions in guided-wave/impedance observables [24]; and SHM implementations should incorporate interface-aware self-diagnostics and/or redundancy-based drift monitoring so that degradation-induced signal changes are not conflated with structural state changes [25,27]. Finally, while accelerated aging and laboratory studies provide mechanistic evidence of interface weakening and signal distortion [23,24], the long-term combined effects of environmental exposure and evolving operational loads remain insufficiently characterized at true infrastructure time horizons, motivating multi-decade validation efforts and standardized reporting of interface durability metrics consistent with life-cycle SHM needs [26].

Life-cycle zero-power sensing [28] are sensors capable of functioning with minimal power requirement over the life of the system to which they are monitoring. For life-cycle zero-power sensing, energy harvesting techniques, material innovations, and advancements in self-sensing materials are gaining attention due to their potential to enhance sensor longevity while reducing maintenance needs. While it is believed that no true life-cycle zero-power sensor for SHM currently exists, the authors aim to conceptualize such a sensor by defining appropriate metrics and evaluating existing systems. The evaluated systems extend beyond the field of SHM to include a wide range of technologies that may not be explicitly considered in the development of sensors for SHM. By rating, rather than ranking, these diverse technologies, this work seeks to draw upon varied concepts from sensing in other application fields. This work initiates a discussion on what would constitute a life-cycle zero-power sensor for SHM by integrating insights from technologies that are near-life-cycle and near-zero-power across different disciplines.

1.1. Research scope and contributions

The motivation of this work stems from the fact that, to the best of the authors’ knowledge, no perfect life-cycle zero-power sensor currently exists. This gap highlights the need for a systematic approach to evaluate and compare the capabilities of existing technologies. In response, this study introduces the novel concept of zero-power life-cycle sensing along with a new classification framework for assessing such systems within the context of structural health monitoring (SHM). The proposed framework is based on five key metrics (measurement, memory reset ability, power efficiency, data transfer, and material integrability), which together provide a structured foundation for quantifying and comparing the zero-power capability of emerging sensing technologies.

To remain consistent with the application domain of interest, SHM, this work focuses on measurement modalities such as load, strain, shock, vibration, temperature, humidity, and moisture, as these parameters provide insight into structural behavior, performance, and environmental conditions influencing long-term aging. The objective is to establish a generalizable framework that streamlines the evaluation and comparison of life-cycle zero-power sensing technologies within this context.

To enable structured and transparent assessment across heterogeneous technologies, five metrics are evaluated using a deliberately discretized 0–2 scale, resulting in a maximum score of 10. The streamlined grading scheme is designed to preserve objectivity, clarity, and comparability rather than to capture every nuanced performance characteristic. Scores are assigned based on the extent to which a study provides clear and measurable specifications of a metric (more relevant), general qualitative statements (relevant), or no explicit information (not relevant). In this way, both quantitative data and qualitative descriptions can be incorporated into a unified scalar measure that reflects the demonstrated potential of a technology to contribute to a life-cycle zero-power sensing system for SHM.

The scientific significance and contributions of this work are twofold. First, five metrics for classifying life-cycle zero-power sensing technologies are introduced into a unified scalar measure to quantify the zero-power capability of a sensing system. Second, state-of-the-art sensor technologies are classified within the newly proposed framework of life-cycle zero-power sensors to identify the key components that can contribute to realizing the conceptualized system. This effort aims to lay the groundwork for advancing zero-power sensing technologies toward practical, life-cycle deployment in SHM applications by identifying critical needs and streamlining the development of these technologies to achieve true life-cycle zero-power sensing.

1.2. Selection of evaluation metrics

In developing a unified framework for assessing life-cycle zero-power sensing technologies, a wide range of evaluation metrics was initially considered. These included power efficiency, data transfer rate, sensing type, physical footprint, reset ability, sampling rate, data integrity, sensitivity, power capacity, standalone operation, recyclability, material integrability, and measurement performance.

During the evaluation process, it was observed that the high number of metrics and their varying degrees of specificity made it challenging to consistently assess existing technologies. Many reported studies did not provide sufficient quantitative or qualitative data to enable explicit conclusions across all categories. As a result, a generalizable framework was required to ensure that the assessment could be applied uniformly across diverse sensing platforms and material systems.

To develop this generalizable evaluation framework, the reduction process involved a systematic review of the initially identified metrics to determine their applicability and consistency across the literature. Metrics that were commonly reported and well-defined in state-of-the-art studies were prioritized, while those that appeared infrequently or lacked standardized measurement criteria were excluded. Additionally, metrics were evaluated based on their clarity in reporting, their ability to reflect fundamental performance characteristics relevant to SHM, and their independence from overlapping parameters. Only metrics that could be reasonably compared or quantified across diverse sensing modalities and operational conditions were retained.

Through this process, it was determined that the following five metrics are the most impactful and representative of the requirements for life-cycle zero-power operation within the context of structural health monitoring:

1. Measurement (sensitivity and event detection)
2. Memory reset ability
3. Power efficiency
4. Data transfer
5. Material integrability

These five metrics collectively capture the essential functional domains that define a sensor's ability to operate autonomously, efficiently, and durably over the full structural life cycle, thereby enabling true life-cycle zero-power sensing.

Measurement sensitivity and event detection consider both the smallest event that the sensor can detect in time and space, and the largest event the sensor will not miss [29]. Memory reset ability determines the sensor's capacity to capture and reset measurements [5]. Some sensors can capture a single event, while others are capable of recording a sequence of events or those with the highest magnitude, providing a historical record of measurements. Data transfer involves the transmission of measured data from the sensor to a processing system [30]. Common methods for data transfer include a mixture of wired and wireless, digital and analog electromagnetic transmission. Other approaches applicable to life-cycle zero-power sensing include optical (e.g., laser-based integration) [31], visual (e.g., camera and remote sensing) [32,33], acoustic [34], ultrasonic [35], infrared [36,37], quantum [38], thermal [39], and vibrational [40] modalities, among others.

The electrical power consumption required to make a measurement plays an important role in the selection of a life-cycle zero-power sensor. The long-term goal is to achieve sensing systems that can be woken up from a passive or nearly passive state while operating in an intelligent standby mode consuming either no power or only minimum power harvested from their environment [41,42]. Material integration refers to the ease with which sensors can be integrated into existing structures [43]. Some sensors are well integrable by utilizing the materials of the structure as part of the sensor itself [44,45]. It can be hypothesized that sensors with a high material integration ability will intrinsically last as long as the structure itself [9,46], thereby enabling life-cycle monitoring.

1.3. Paper organization

The remainder of this work consists of four main chapters. A methodology chapter outlines the proposed framework, evaluation approach, and metrics. This is followed by a review chapter of existing zero-power sensing technologies, their classification according to the defined metrics, and presents the results of applying the framework to those technologies. Chapter Four is a discussion chapter that summarizes the research needs and the authors' perspective in the context of long-term SHM applications. Finally, the work concludes with an overview of contributions and perspectives on future research directions.

2. Methodology

To clarify the objectives and contributions of this study, we aim to establish a structured, interdisciplinary framework for evaluating the potential of emerging sensor technologies to meet the stringent requirements of life-cycle zero-power sensing in structural health monitoring (SHM). Our scientific contribution lies in formalizing five critical evaluation metrics – measurement sensitivity, memory reset ability, power efficiency, data transfer, and material integration – and applying them systematically across nine representative case studies drawn from diverse domains, including MEMS, optomechanics, soft robotics, and passive RFID. These examples were not selected arbitrarily; rather, they were chosen based on their novelty, demonstration of one or more zero-power features, and potential relevance to SHM applications. While these technologies originate from various fields, they were selected for their ability to inform design principles for future SHM systems that must operate passively over decades without maintenance. Importantly, our framework does not claim equivalence across modalities (e.g., thermal vs. dynamic sensing) but instead focuses on relative readiness across each metric, highlighting strengths and gaps. By rating – rather than ranking – these technologies, we emphasize that different sensing modalities serve complementary roles within the SHM ecosystem and thus require separate yet harmonized evaluation.

2.1. Definition of a life-cycle zero-power sensor

To the best of the authors' knowledge, no perfect life-cycle zero-power sensor exists. An ideal life-cycle zero-power sensor is:

1. A sensor that can function durably over the structure's life-cycle without planned maintenance,
2. A sensor that requires near-zero power to perform its sensing function,
3. A sensor that maintains a memory state of the structure and supports on-demand access that can provide historical information at any time throughout the structure's life-cycle.

Structural life-cycle encompasses the entire operational period of a structure without major modifications, with continuous monitoring from construction to end-of-life to enable early problem detection and insights into aging and deterioration. [10]. Life-cycle zero-power sensors could be used to detect changes or anomalies in the structure, for example, to identify potential issues such as cracks, corrosion, or overstress. This aids in avoiding structural failure and enabling more accurate scheduling of preventative maintenance [47,48].

The authors define the boundary of zero-power sensing as the point where information is transferred beyond the location of the sensed stimulus, as illustrated in Fig. 2. Such systems include a sensing element, a mechanism to efficiently extract stimuli from the sensor, a memory structure to retain the data, and a method to transfer this data away from the sensing location once the sensing system is interrogated. This definition excludes the receiving end of the interrogation method and any subsequent systems from the scope of this work. Fig.

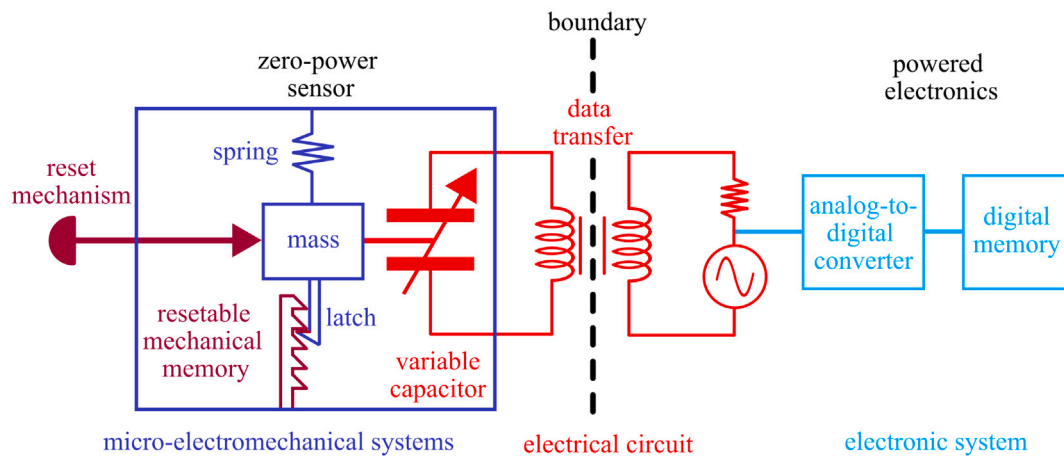


Fig. 2. An example of wireless sensing technology that constitutes a potential life-cycle zero-power sensor with the sensing boundary considered in this paper annotated.

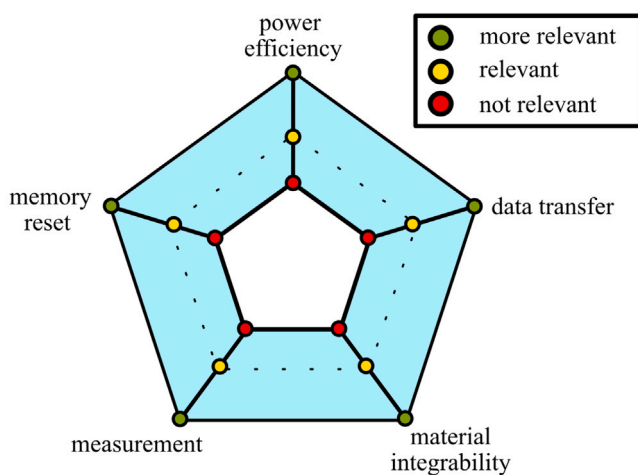


Fig. 3. Visualization of the proposed evaluation methodology based on the five key metrics that define an ideal zero-power sensor.

2 illustrates an example of a conceptual zero-power sensing system adopted from a MEMS-based technology presented by Reddy et al. [5]. It includes a mass-spring shock-sensing element to take measurements, a mechanical memory-holding structure that converts shock magnitude into a memory state, and a data transfer element presented through the natural resonance of a coupled inductor-capacitor. As shown in the simplified example presented in Fig. 2, the measurement occurs passively with no reliance on electric power, with the sensing boundary defined as the dashed line where the data is transferred outside the location in which it was sensed.

Importantly, this work constitutes a validated prototype case study of the proposed framework. The authors designed, fabricated, and experimentally tested a 5 mm² MEMS shock sensor capable of recording 10 discrete acceleration thresholds over a 20–250 g range without any power consumption during sensing or memory retention [5]. Approximately 200 controlled impact tests were performed, demonstrating agreement within ±2 g of the numerical model and confirming reliable passive latching and reset functionality. This implementation directly reflects the framework elements defined here: passive stimulus extraction, intrinsic mechanical memory, and post-event data retrieval, thereby demonstrating its practical applicability to structural health monitoring scenarios where long-term, zero-power event recording is required.

Scoring consists of three categories

1. More relevant: The work explicitly reports clear and measurable specifications or procedures of the examined metric.
2. Relevant: The work generally states information, methods, or procedures relating to the examined metrics.
3. not relevant: The work does not explicitly state any information regarding the specific metric in question.

The remainder of this section introduces the five metrics defined by the authors for quantifying zero-power sensing. These metrics are visualized in Fig. 3 and defined in what follows.

2.2. Measurement (sensitivity and event detection)

Together, sensitivity and event detection are fundamental for providing a comprehensive understanding of the monitored environment, supporting timely interventions, and ensuring structural integrity. Sensitivity in sensors refers to their ability to detect small changes or differences in the measured quantity or parameter [49], which is often quantified as the ratio of the output signal change to the input physical quantity change, with higher ratios indicating greater sensitivity. High sensitivity means the sensor can respond to minute variations in the input, making it crucial for applications requiring precise and accurate measurements. For example, in SHM, sensitive transducers can detect small changes in structural conditions, aiding in early damage detection and maintenance planning.

Event detection, on the other hand, involves identifying specific occurrences or changes in the monitored parameter over time. In SHM, this can include tracking maximum, minimum, mean, and standard deviation values to summarize the behavior of the structure during a specified period. Effective event detection relies on the sensitivity of the sensors to accurately capture these changes, enabling the identification of anomalies or critical events that might indicate structural issues.

Relevant examples of sensors include the work on a piezo-based four L-shaped beam by Shi et al. [50], which presents an accelerometer with a sensitivity of 28.14 mV/g at 500 Hz. This sensitivity was achieved by utilizing a 1 μm lead zirconate titanate film manufactured using sol-gel methods. Another study by Luo et al. [51] introduces a bio-inspired soft sensor array that enables large-footprint sensing which consumes 442.4 nW of power at a load resistance of 0.5 GΩ with a voltage to side-length dependency of 1.58 V/cm. In this work, the authors also define material sensing as the capability of a sensor to identify and distinguish the intrinsic material properties of contacting objects, achieved by analyzing triboelectric signals that vary according to the material's electron affinity, independent of pressure or contact area.

2.3. Memory reset ability

Single-use event-detection sensors are characterized by their irreversible functional design, which precludes them from being reused or reset after initial deployment. These sensors are typically designed to take critical measurements where the sensing element undergoes a permanent chemical or physical change upon exposure to the target condition [52]. Such conditions typically exhibit high dynamic changes like shock and temperature peaks. This irreversible change ensures high specificity and accuracy for the intended measurement but renders the sensor inoperable for subsequent use. In contrast, sensors with memory reset ability are engineered to retain or revert to their baseline state after data acquisition, allowing for multiple usage cycles. This reset ability is often facilitated by incorporating memory elements that can be electronically or physically reset. Such sensors are essential in applications requiring repetitive, continuous data collection, such as process control, structural health monitoring, or long-term environmental surveillance.

Proposed by Reddy et al. [5], a system that utilizes a MEMS-based mass-spring structure that measures peak acceleration. Relying on the elastic properties of the MEMS structure, the authors devised a mechanical latching system that holds the state of the measurement while requiring zero power. Additionally, a reset structure was also integrated into the design to allow the sensor to return to its original state once the historic measurement is no longer needed. For a footprint of 5 mm², the shock sensor was reported to have 10 threshold levels to detect an acceleration range of 20 g–250 g, with the ability to reset measurements by releasing the latch mechanism. The authors reported a quality factor of 24 with a resonant frequency of 822 Hz, further proving the technology as a zero-power alternative to electronic shock and vibration monitoring systems currently in use.

The work by Lake et al. [53] demonstrated that a multi-mode optomechanical system coupled with an auxiliary field significantly extended the memory decay time by an order of magnitude and reduced the effective mechanical dissipation rate by two orders of magnitude through parametric feedback. In resonance-based memory devices, the memory storage time is a function of the signal-to-noise ratio, which dictates when the resonance becomes too low to be distinguished from noise. Experimentally, the authors reported a memory decay time of 7.7 μ s. With an SNR of 1000, they predicted that a memory decay time of 5 ms could be achieved. Additionally, they showed the ability to deterministically shift the phase of a stored field by over 2π , enabling increased information storage and precise signal processing within the optomechanical system.

Another approach to memory holding is demonstrated by Nemitz et al. [54] using a bistable membrane that allows permanent memory storage of binary information without the need for electronics. This technology utilizes the interaction between atmospheric pressure and a control input of 8 kPa to not only store binary bits but also conduct logic computation by configuring multiple membranes. In both approaches, the authors deviate away from electronic memory by relying on long-lasting vibrations or material properties to solve the zero-power challenge of memory holding and reset ability.

2.4. Power efficiency

Power efficiency is a critical consideration in sensing systems, as it directly impacts the performance, efficiency, and lifespan of sensors [55]. In the context of power consumption, three scenarios are particularly relevant: sensing, data transmission, and memory. Sensing power consumption refers to the power required by the sensor to perform measurement operations. It can be categorized into active sensing, which includes powered and ultra-low power systems, and passive sensing, which utilizes mechanical or chemical means to take measurements. Data transmission power consumption relates to the power needed to transmit measurement data from the sensor to the

processing system. This power requirement is highly dependent on the type of data and the method by which it is transferred. Wired systems are generally more efficient, as the signal is passed through a conducting medium, whereas wireless transmission uses electromagnetic waves that require more power to transmit. Memory power consumption is another consideration, as sensors often require memory to store captured measurements. The power required for memory storage can vary depending on the type of memory used, which includes electrical memory (volatile or non-volatile), mechanical memory, or chemical memory.

Zero-power refers to a state in which a system consumes no electrical power to operate. Zero-power components are often desirable in devices that operate in restrictive power consumption environments, where they can significantly extend operational lifespan. The defined threshold for zero-power sensing is considered to be in the sub-micro-watt range [41]. In a sensing framework, this is defined as the power needed for a sensing system to remain operational in an intelligent standby mode. Such systems rely on ultra-low power electronics [56] or mechanical [5] methods to take measurements without requiring electrical power. Near zero-power data transfer [57] refers to the process of transmitting information between two systems using power in the nano- to micro-watt range. This is typically achieved through the use of low-loss electrical circuits over short distances. Short-range radio frequency identification (RFID) [5] is one of the most widely used ultra-low power systems due to its simplicity and reliability. The power consumption of electronics on the receiving end can vary significantly depending on their applications and operational needs. Therefore, this paper defines the boundary of zero-power sensing as the point at which information leaves the physical location of measurement, as detailed in Fig. 2.

In the work presented by Cassella et al. [58], a MEMS-based switching receiver is described, featuring a solid-state envelope detector designed to function as a fully passive RF wake-up receiver. By utilizing a MEMS cantilever switch as a resonator, the excitation frequency can reach as high as 75.3 kHz, with a quality factor of 4700. This work reports a high sensitivity of -60 dBm while consuming no power in standby mode. Additionally, the paper by Benbuk et al. [59] presents a framework for extending sensor network operational lifespan to near self-sustainability by combining RF energy harvesting and wake-up circuits. The authors report a current consumption of 13 μ A in processing bit sequence mode and as low as 0.2 nA when the device is in listening mode. These technologies aim to extend the operational life of sensing systems by optimizing power consumption across sensing, data transmission, and memory storage, which is key to achieving a longer lifespan in structural health monitoring (SHM).

2.5. Data transfer

Data transfer is a fundamental aspect of sensing systems, enabling the communication of measurement data from sensors to the processing system for analysis and decision-making [60]. Data transfer can be achieved through wired or wireless methods. Wired data transfer involves the use of physical connections, such as electric or optical lines. Electric transmission utilizes electrical cables through analog or digital protocols to transfer data, while optical transmission uses optical fibers for transmission in the form of light signals. Favorable attributes of wired data transfer are the high transmission rates and reliability, as the physical contact minimizes unwanted interference; however, in some applications involving long transmission distances or hard-to-reach locations, wired systems become costly and highly complex to install and maintain. Alternatively, wireless data transfer eliminates the need for physical connections and utilizes wireless technologies such as radio frequency, acoustic, or optical means. RF transmission involves the use of radio waves to transmit data, while acoustic transfer utilizes sound waves, and optic transmission employs light signals for data transfer. Such approaches perform exceptionally well in stand-alone

sensing systems and applications involving long-distance transmission; however, they are highly susceptible to interference and jamming due to environmental or human intervention. Additionally, wireless systems typically operate at lower transmission speeds than their hard-wired counterparts.

Optical means of data transfer offer a line-of-sight solution where information can be encoded into a color-changing medium that is observed by optical cameras within the visible light spectrum. Liu et al. proposes [61] an elastic sensing skin that boasts strain-induced color-changing properties. The authors report the smallest detectable crack length to be 0.84 mm with an optical gauge factor of 0.53 within 0–30° viewing angle, indicating the angle-independent color change property of the sensor. Given the large footprint and the desirable optical properties, this technology offers a solution for line-of-sight data transfer, eliminating the need for powered wireless transmission.

Zhu et al. [62] demonstrate wireless data transfer through a passive electromechanical system. The setup includes a temperature sensor using a bimetallic coil mechanically coupled to a passive RFID encoder. This encoder acquires a 6-bit binary code, which is then transmitted via an RF circuit powered by an energy harvester. The system boasts a sensitivity of 1.32 °C/bit and can operate over a distance of more than 10 m, highlighting its potential for zero-power data transfer applications.

For longer distances (several kilometers) with minimal power consumption, the option of infrared transmission emerges as a promising solution. Spitz et al. [36] propose an infrared interband cascade laser operating in the 4 μm atmospheric transparency window. The authors achieved transmission rates up to 300 Mbits/s with a return-to-zero scheme at room temperature. With the longer wavelength of the interband cascade laser, this technology offers an energy-efficient free-space infrared communication framework that can enhance the transmission range of life-cycle sensors.

2.6. Material integration

Material integration in sensor design involves combining various materials and components into a unified sensing system. Using the measured medium as part of the sensing structure is crucial for minimizing physical footprint, weight, and power consumption while achieving a highly integrated sensor [63]. Multi-modality of measurement is particularly beneficial in contact sensing applications, where the sensor interacts physically with the target environment. This requires a design that not only responds to stimuli with minimal interference but also withstands direct physical contact with the measured stimuli without compromising functionality. Equally important is the recyclability of sensor materials, as demonstrated in recent work on flexible multimodal devices. Sensors fabricated from polyvinyl alcohol (PVA), choline chloride, and ethylene glycol with micro-pyramidal structures can be completely dissolved in water and reprocessed into new sensing films. These devices maintain stable performance for pressure, temperature, and humidity detection after at least five full recycling cycles, highlighting a sustainable pathway to reduce electronic waste while preserving sensing functionality [64].

In long-term structural health monitoring, sensors must be well integrated into the structure. This integration shields the sensing elements and allows damage detection deep within the structure. Nalon et al. [65] investigated self-sensing concrete masonry structures, focusing on using mortar joints as an integrated sensing medium. Their findings indicate that fractional changes in electrical resistivity under plastic deformation prove the ability of these self-sensing joints to indicate stress/strain damage and masonry modes of failure. For temperature sensing of non-uniform structures, flexible, large-footprint sensors emerge as a great solution. The work by Shin et al. [66] presents an artificial sensing skin using monolithic selective laser reductive sintering that forms a temperature-sensitive membrane with excellent

sensing qualities. The authors report a material constant of their thermistor to be 7350 K for the overall measuring range of 25–70 °C and a high material constant of the thermistor, up to 8162 K at room temperature. With desirable temperature sensitivity and flexibility, these sensors can be easily integrated for precise temperature sensing applications of non-uniform and dynamic objects that require accurate temperature mapping.

Beyond traditional sensors, new developments incorporate smart materials such as multifunctional materials fabricated using carbon nanotubes or piezoelectric elements. These materials enable the structure to self-sense and report changes, reducing the need for extensive external sensing systems [67]. Such integration improves the overall durability of the sensor and ensures that the system remains reliable even in harsh environmental conditions [68], which also enhances real-time feedback and enables structures to be more intelligent and responsive to internal changes, further extending the lifespan and robustness of SHM applications.

2.7. Review summary of key metrics

The reviewed subsections highlight five essential metrics that together define the effectiveness of life-cycle zero-power sensors. First, *measurement sensitivity and event detection* ensure early and accurate identification of structural changes, supporting preventative maintenance. Second, *memory reset ability* distinguishes reusable sensors from single-use devices, enabling long-term monitoring by allowing data retention and reset functions. Third, *power efficiency* is critical for sustainability, with zero-power or near-zero-power operation extending sensor lifespan across sensing, transmission, and memory tasks. Fourth, *data transfer* methods, whether wired or wireless, determine how effectively measurement results are communicated, with passive and energy-efficient approaches showing promise for structural health monitoring. Finally, *material integration* emphasizes embedding sensors directly into structural materials, enabling durability, multifunctionality, and even recyclability, while minimizing system footprint. Together, these metrics form the evaluation framework for assessing current technologies and guiding progress toward practical life-cycle zero-power sensing systems.

3. Analysis of sensor technologies for life-cycle zero-power structural sensing

This section reports on the classification of existing sensing technologies that meet some or all of the sensing criteria defined in this work. The selection of the nine papers in this study is based on their representation of key advancements in life-cycle zero-power sensing, contributing to the five evaluation metrics demonstrated above. These papers were chosen for their innovative approaches to passive sensing, low-power technologies, sensor integration, and durability. The selection includes diverse sensing modalities, representing a comprehensive analysis across different application areas in SHM. The technologies examined are evaluated based on their relevance to life-cycle zero-power sensing, power efficiency, data transfer, integrability, sensitivity, and memory reset ability. A scale from 0–2 is used, ranging from “not relevant” to “more relevant”, and the total relevance score is reported out of 10 points. To be considered, These sensing methods required a score of at least 5 points and no more than two metrics deemed not relevant for the literature to be considered.

3.1. High-sensitivity wearable temperature sensor enabled by monolithic integration

Shin et al. [66] presents an artificial temperature-sensing skin through a monolithic laser-induced reductive sintering scheme, along with using unique monolithic structures. Such structures have a favorable thermal activation mechanism attributed to the monolithic

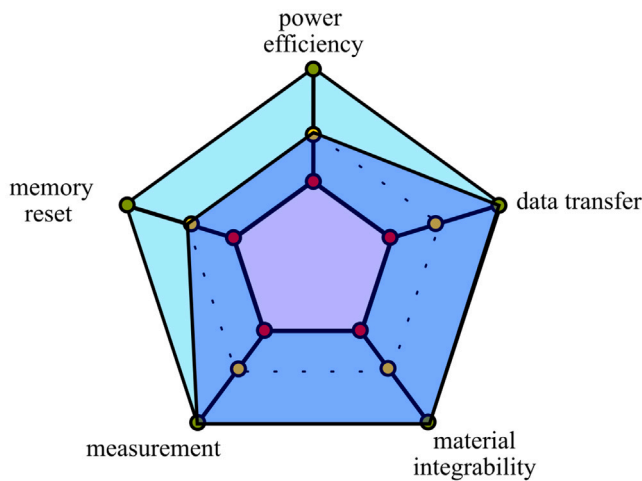


Fig. 4. Score chart of “Sensitive Wearable Temperature Sensor with Seamless Monolithic Integration” for the five considered evaluation metrics.

laser reductive sintering process. Given its desirable properties, this technology is shown to have applications in soft robotics, artificial prosthetics, and large-footprint self-sensing structures for structural health monitoring applications. The authors integrate two types of materials, a metal electrode and a metal oxide sensing channel, claiming that this combination enables the highest temperature sensing ability reported amongst negative temperature coefficient thermistors. This highly sensitive thermistor is constructed through a Ni metal electrode and NiO sensing channel in a Ni-NiO-Ni configuration, where the sensitivity and response time of the thermistor are found to be a function of the NiO layer thickness. This temperature-sensing method also demonstrated a desirable response time of 50 ms during testing, further contributing to its desirable use in highly dynamic temperature-sensing applications. Fig. 4 presents a total score of 8 over the five evaluation metrics for the work by the authors on sensitive wearable temperature sensors, while Table 1 details the rationale behind the scoring.

1. **Measurement (sensitivity and event detection):** With a thin Polyethylene Terephthalate base film thickness of 25 μm , allowing the reduction of thermal mass, this sensor exhibits an exceptional response time of 50 ms, making it optimal for event detection. The authors report the sensitivity of the monolithic laser reductive sintering NiO temperature sensor to be $-9.2\% \text{ } ^\circ\text{C}^{-1}$ at 25 $^\circ\text{C}$. The linear measurement range of this sensing technology is reported to be between 25–70 $^\circ\text{C}$. The sensitivity of the NiO is reported using the relationship shown in (1) where R_∞ , T , and B are the reference resistance of the sensor, temperature, and the material constant of the thermistor, respectively.

$$R(T) = R_\infty e^{B/T} \quad (1)$$

Where the material constant of the thermistor is reported to be 7350 K over the whole measurement range and 8162 K at room temperature, indicating an exceptionally high sensitivity among thermistor-based temperature sensors.

2. **Memory reset:** Utilizing a Ni-NiO-Ni negative temperature coefficient thermistor, this sensing technology does not possess any memory-holding structures to indicate historical data for temperature; however, due to the sensor’s resistive nature, the substrate is shown to be resettable without the need for it to be altered or reconfigured to take the next measurement.
3. **Power efficiency:** This sensing technology relies on a temperature-dependent resistive substrate and is driven by a source meter, which applies a constant current and calculates the sensor’s temperature-dependent resistance by observing the

temporal change in voltage. The electrical resistance along with the material constant of the thermistor is reported as a function of the NiO channel width, in μm , of the Ni-NiO-Ni negative temperature coefficient thermistor. With the sensor’s resistivity indicated in the $\text{M}\Omega$ range, the sensor exhibits a very small current consumption during measurement, which further increases its efficiency as a high current can alter the temperature of the sensor itself, decreasing its signal-to-noise ratio.

4. **Data transfer:** The NiO channel negative temperature coefficient thermistor is reported to have a response time of 50 ms. This refers to the time it takes from introducing a known heat source till the sensor observes that given temperature. Due to this sensing technology’s analog nature, the output is a continuous analog signal fed into a source meter. In this context, a hard-wired means of transfer is reported as this negative temperature coefficient thermistor requires a current supply to operate.
5. **Material integrability:** Fabricating the sensors on a 25 μm layer of Polyethylene Terephthalate with the monolithic contact between the Ni electrodes and the NiO sensing channel provides an alignment-free, single-step process, ensuring a highly compact sensing unit with improved contact quality. Furthermore, laser-induced reductive-rapid thermal annealing is reported to provide a low-heat-budget method for NiO sensing channel activation. From the small footprint with thicknesses in the range of 55 μm , including the Polyethylene Terephthalate base film, to the innovative activation mechanism using reductive-rapid thermal annealing, this type of negative temperature coefficient thermistor is shown to have superior responsiveness while mitigating any material compatibility challenges that arise in conventional annealing processes, typically experienced when manufacturing flexible substrates.

3.2. In-sensor computing through materials and device integration

Wan et al. [69] propose in-sensor computing as an efficient method to address the challenges attributed to real-time data processing in data-intensive applications. In-sensor computing integrates computing operations into a sensing unit or an array of sensors. This approach processes information during the transition period from event detection to electronic signals. With this approach, the sensing system can significantly cut down on redundancy in the data where external stimuli of multiple sensors are processed into features, thereby reducing the amount of data transferred and the computational load required at the central processing unit. This decentralized computing approach allows for higher energy efficiency and reduced latency as some of the data processing is done during signal transit. This technology addresses computing functions on two fronts, at the device and array levels. At a device level, this method exploits the response characteristics of the sensing unit to execute operations and process stimuli. On an array level, the computing ability of a group of sensors is used to transform the array element into a sensing and computing unit. This approach enhances parallelism by making use of the simultaneous interaction between sensing units with external stimuli, further increasing speed and processing efficiency. Fig. 5 presents a total score of 6 over the five evaluation metrics for the work by the authors on in-sensor computing, while Table 2 details the rationale behind the scoring.

1. **Measurement (sensitivity and event detection):** Given an array element, measurements can be taken through multiple sensors, with processing being done both on device and array levels simultaneously. This framework of decentralized computing significantly limits the need for large amounts of data to be transferred beyond the array element. Furthermore, utilizing the array structure as a computing unit, some operations can be executed by simply passing the signal through the architecture.

Table 1
Summary of classification scores and main characteristics for each evaluation metric (Shin et al. [66]).

Metric	Main Characteristics	Score (0–2)
Measurement	Response time of 50 ms; sensitivity of $-9.2\% \text{ } ^\circ\text{C}^{-1}$ at $25 \text{ } ^\circ\text{C}$; linear range $25\text{--}70 \text{ } ^\circ\text{C}$; thermistor constant 7350–8162 K indicating high sensitivity.	2
Memory reset	Resistive nature allows reset without reconfiguration; no historical data storage.	1
Power efficiency	Operates with small current consumption ($M\Omega$ resistivity range); constant current source avoids self-heating and preserves SNR.	1
Data transfer	Continuous analog output; response time 50 ms; requires hardwired means of transferring information	2
Material integrability	Fabricated on $25 \text{ }\mu\text{m}$ PET; compact ($55 \text{ }\mu\text{m}$ total thickness); alignment-free monolithic contacts; low-heat laser annealing enables flexible substrate compatibility.	2

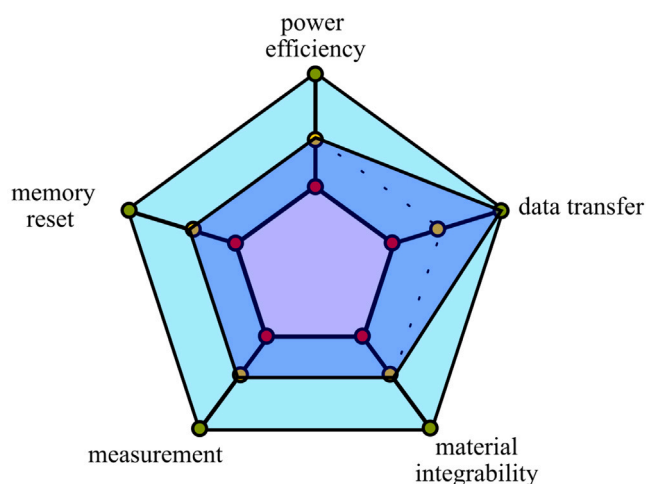


Fig. 5. Score chart of “In-sensor Computing: Materials, Devices, and Integration Technologies” for the five considered evaluation metrics.

This has the benefits of low latency and energy efficiency, as significantly less data is needed to be sampled and processed later on due to the high complexity of the in-sensor computing paradigm.

- 2. Memory reset:** With the inherent computing nature of such a framework, the computing architecture can recognize features in the data and hold on to them for comparison with subsequent measurements, effectively forming a memory-holding structure that resets by the flow of more data that carries a different set of features.
- 3. Power efficiency:** By responding to external stimuli through arrays of sensing elements while executing computational operations on the device and array levels simultaneously, this system offers a high level of parallelism, contributing to a significant reduction in power demands. By utilizing the architecture itself to realize processing operations otherwise done by a central processing unit after analog-to-digital conversion of large amounts of data, a power-efficient method is achieved. This work does not report on the amount of power saving offered by this approach due to the generalized system adopted in the literature.
- 4. Data transfer:** Using feature enhancement functions close to the sensing terminals, the sensing array can distinguish patterns in the data and reduce redundancy. With this approach, the workload of the subsequent processing units is reduced, thereby trimming down the overall amount of data transfer required to execute the same operations typically done by a centralized processing unit. For instance, operations like matrix summation, an essential step in sensor array data fusion, are directly realized in hardware by utilizing Kirchhoff's laws. In addition, by embedding computing functions into the sensor itself, redundant raw data streams no longer need to be transmitted for conversion and external processing. This integration minimizes

latency, alleviates bandwidth bottlenecks, and enhances energy efficiency, while simultaneously lowering the risk of security vulnerabilities often associated with frequent data transmission between separated units.

3.3. Polysaccharide-based optical sensors for metal ion detection

Azeman et al. [70] focus on utilizing polysaccharides, specifically chitosan and carrageenan, as sensing materials in optical sensor applications for detecting metal ions. These polysaccharides are chosen for their bio-based nature and remarkable physicochemical properties, which make them suitable for interacting with target analytes through various mechanisms such as chelation, electrostatic interaction, and hydrogen bonding. The application of the system involves designing and fabricating optical sensors that incorporate polysaccharides as the active sensing layer. These sensors are used for the selective detection of specific metal ions like Pb^{2+} , Cd^{2+} , and Hg^{2+} in various samples. The interactions between the polysaccharides and the target analytes enable the sensors to exhibit high sensitivity and selectivity towards the detection of these metal ions. The system was experimentally tested and verified through studies that involved the development of optical fiber sensors based on surface plasmon resonance and other techniques. These sensors were coated with polysaccharide composites, such as pyrrole/chitosan, and tested for their ability to detect metal ions. Experimental setups were used to measure the sensitivity and detection limits of the sensors, demonstrating the effectiveness of the polysaccharide-based sensing materials in detecting metal ions with high precision and accuracy. Fig. 6 presents a total score of 4 over the five evaluation metrics for the work by the authors on Polysaccharides as a sensing material, while Table 3 details the rationale behind the scoring.

- 1. Measurement (sensitivity and event detection):** The polysaccharide-based optical sensors demonstrate high sensitivity and low detection limits, showcasing excellent measurement performance for detecting metal ions. For instance, carboxymethyl chitosan–quantum dots achieved Zn^{2+} detection down to $4.5 \text{ }\mu\text{M}$ and lysozyme at 0.031 ng mL^{-1} , while chitosan/AuNP@S-g- C_3N_4 composites enabled Hg^{2+} detection at an ultralow limit of 0.275 nM . Carrageenan-based systems also showed competitive performance, with Cu^{2+} detected at $1.7 \text{ }\mu\text{M}$ and S^{2-} at $2 \text{ }\mu\text{M}$. Such results underline the effectiveness of polysaccharide composites in colorimetric sensing. For obtaining a good surface plasmon resonance performance, Ag produces better detection accuracy compared to Au when employed as a thin metallic film at the interface of two dielectric media in the Kretschmann configuration.
- 2. Memory reset:** The information regarding the reliable reset ability of polysaccharide-based optical sensors is not explicitly mentioned. No memory-holding structure or system to retain the polysaccharide sensor measurement.

Table 2

Summary of classification scores and main characteristics for each evaluation metric (Wan et al. [69]).

Metric	Main Characteristics	Score (0–2)
Measurement	Array/device-level processing; decentralized computing; low latency and energy-efficient detection.	1
Memory reset	Feature memory structure reset by incoming data with new features.	1
Power efficiency	Parallel processing reduce power; avoids centralized data handling (savings not quantified).	1
Data transfer	On-sensor feature extraction; reduced redundancy; basic operations via array (e.g., Kirchhoff's laws).	2
Material integrability	Multi-stimuli sensing (light, sound, magnetic, chemical); compact and versatile for SHM/biological monitoring.	1

Table 3

Summary of classification scores and main characteristics for each evaluation metric (Azeman et al. [70]).

Metric	Main Characteristics	Score (0–2)
Measurement	High sensitivity and low detection limits for metal ions (e.g., Zn^{2+} 4.5 μ M, Pb^{2+} 1.7 μ M, Hg^{2+} 0.275 nM); Ag films provide better accuracy than Au in SPR configuration.	2
Memory reset	No explicit reset mechanism; no memory-holding structure reported.	0
Power efficiency	Near-zero power consumption due to passive optical sensing with polysaccharides with no explicit information stated	1
Data transfer	Not addressed; focus on sensing material performance rather than signal transfer.	0
Material integrability	Chitosan/carrageenan enhance analyte interaction; tunable properties via modification; challenges remain in long-term stability and attachment.	1

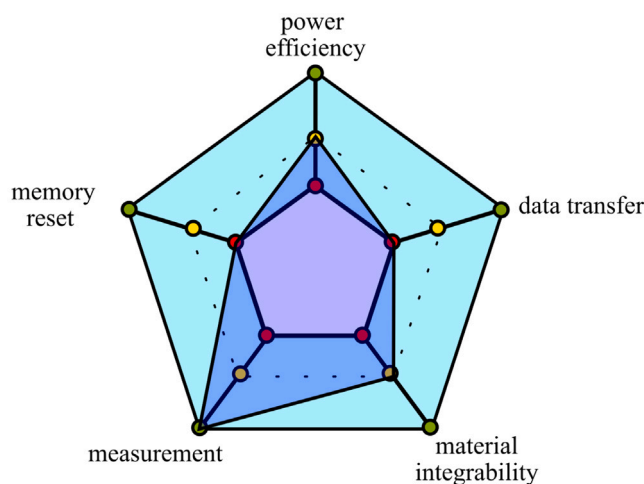


Fig. 6. Score chart of “Polysaccharides as the Sensing Material for Metal Ion Detection-Based Optical Sensor Applications” for the five considered evaluation metrics.

- Power efficiency:** By adopting a novel approach to manufacturing sensing nodes and leveraging the desirable properties of polysaccharides, the integration of polysaccharides with optical sensing techniques allows for near-zero power consumption during sensing operations.
- Data transfer:** The paper primarily discusses the selection, modification, and application of polysaccharides as sensing materials in optical sensors for detecting metal ions. There is no mention of data transfer.
- Material integrability:** The integration of polysaccharides, such as chitosan and carrageenan, with optical sensing techniques enhances sensor performance for metal ion detection. By modifying polysaccharides physically and chemically, their properties can be tailored to specific sensing applications, improving interaction with target analytes. While polysaccharides offer advantages in sensor applications, challenges such as long-term stability and sensor surface attachment need further research for commercialization.

3.4. Integrating machine learning with bio-inspired soft sensor arrays

Luo et al. [51] present a bioinspired soft sensor array that works by integrating pressure and material sensing capabilities based on the triboelectric effect. The sensor array consists of cascaded row + column electrodes embedded in low-modulus porous silicone rubber, allowing it to capture rich information from the environment. This information is then analyzed by data-driven algorithms, such as multilayer perceptrons, to extract higher-level features for tasks like individual and object recognition. The application of this array-based sensor includes individual recognition of users based on keystroke dynamics, as well as object recognition tasks such as identifying the placement and extraction of objects with different materials, sizes, and shapes. The sensor array was experimentally tested and verified through the following methods: First, *Individual Recognition*: Leveraging a support vector machine, the sensor was tested for individual recognition of users based on their single-pixel keystroke dynamics, achieving a high accuracy rate of 98.9%. Second, *Object Recognition*: A large-scale dataset of multipixel sensing maps (4000 frames) recorded by the BOSSA when manipulating 10 objects was used to test object recognition capabilities. Assisted by a multilayer perceptron model, the bioinspired soft sensor array successfully recognized the placement and extraction of 10 objects with different materials, achieving an accuracy rate of 98.6%. Examples of the objects used for training and recognition include a key, a lipstick, a fruit (mango, lemon, litchi, banana), and an identification card. Fig. 7 presents a total score of 7 over the five evaluation metrics for the work by the authors on a bioinspired soft sensor array, while Table 4 details the rationale behind the scoring.

- Measurement (sensitivity and event detection):** The bioinspired soft sensor array exhibited stable performance with minimal drift even after 20,000 contact–separation cycles. Electrical tests showed the open circuit voltage of porous silicone rubber increases from approximately 0.05 V at 0% NaCl to 0.11 V at 50% NaCl, confirming an enhanced signal output due to NaCl integration. Electrically, the triboelectric open-circuit voltage (Voc) of a 5 cm × 5 cm unit depended on applied force (e.g., 0.5 N) and frequency, while outputs varied with load resistance. Incorporation of NaCl microparticles improved both mechanical and electrical responsiveness, supporting scalable high-resolution sensing for intelligent monitoring applications.

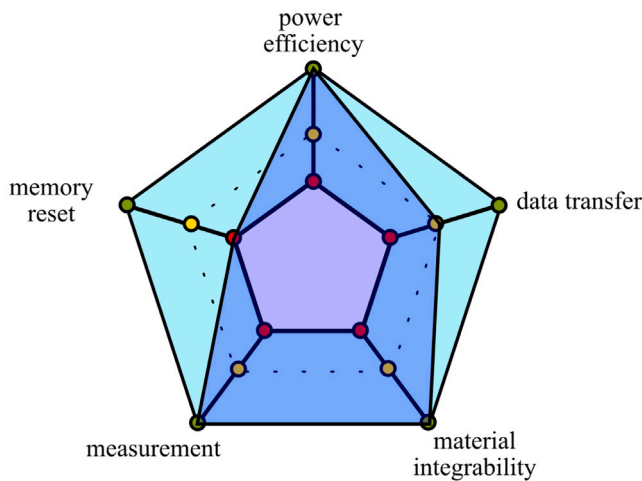


Fig. 7. Score chart of “Machine-Learning-Assisted Recognition on Bioinspired Soft Sensor Arrays” for the five considered evaluation metrics.

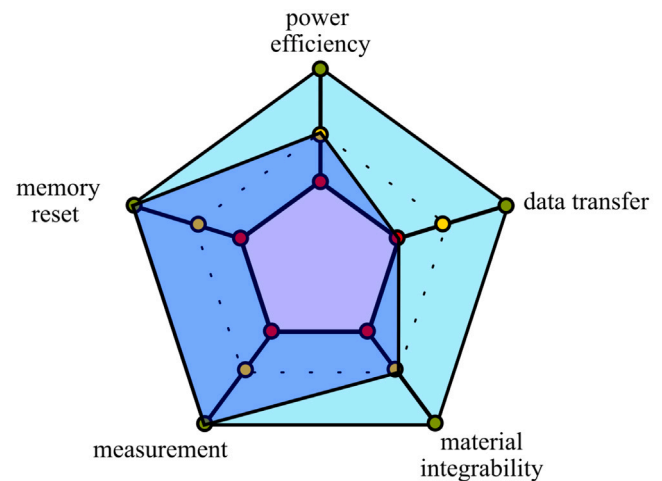


Fig. 8. Score chart of “Processing Light with an Optically Tunable Mechanical Memory” for the five sensing technologies’ evaluation metrics.

2. **Memory reset:** The bioinspired soft sensor array system exhibits the ability to continuously take measurements, allowing it to maintain consistent and reliable performance in prolonged-use applications. There was no explicit mention of memory holding or sensor reset ability covered in this work.
3. **Power efficiency:** The sensing power consumption of the bioinspired soft sensor array system is optimized to be low, with efficient utilization during signal acquisition. Electrical characterization showed that the sensing current is on the order of 10–40 nA under the resistance range of $\sim 10^3$ – $10^9 \Omega$, with an instantaneous peak power of 442.4 nW achieved at a resistance of 0.5 G Ω , confirming efficient energy transfer with minimal losses.
4. **Data transfer:** The conditioned signals were relayed to the onboard RF transceiver, facilitating wireless communication in the bioinspired soft sensor array system for real-time data transfer, monitoring, and analysis with no new technology being presented for low-power alternatives of data transfer.
5. **Material integrability:** The material integrability of the bioinspired soft sensor array benefits from the tunability of porous silicone rubber mixed with NaCl microparticles. Mechanical tests showed that the Young’s modulus decreases with less NaCl integration from 0.08 MPa at 50% NaCl to 0.04 MPa at no NaCl, enhancing softness and deformability for improved conformal contact at the expense of the sensitivity in the electrical response. This tunability introduces functional trade-offs: lower NaCl content maintains higher stiffness and durability but reduces charge density, while higher NaCl content increases electrical output and sensitivity at the expense of mechanical robustness. Such controllable characteristics enable scalable fabrication of sensing units optimized for different application requirements.

3.5. Optically tunable mechanical memory for light processing

Lake et al. [53] investigate the storage of optical signals in long-lived mechanical vibrations memory using optomechanically induced transparency and dynamic reservoir engineering. In this system, information is stored within the degrees of freedom of a micro-mechanical system. Additionally, the authors explore processing the data through an optical field coupled to the memory, altering its dynamics through time-varying parametric feedback. By achieving desirable features such as extending the memory decay time by an order of magnitude, decreasing the effective mechanical dissipation rate by two orders of

magnitude, and deterministically shifting the phase of a stored field by over 2π , this work significantly expands the tools available for optomechanical-based memory storage and data processing. Fig. 8 presents a total score of 6 over the five evaluation metrics for the work by the authors on processing light with an optically tunable mechanical memory, while Table 5 details the rationale behind the scoring.

1. **Measurement (sensitivity and event detection):** Using diamond microdisks as multimode cavity optomechanical systems, the optical mode ($\omega_a/2\pi = 197$ THz, $\kappa_a/2\pi = 0.856$ GHz) is coupled by radiation pressure to the mechanical radial breathing mode ($\omega_b/2\pi \approx 2.14$ GHz, $\Gamma_b/2\pi = 190$ kHz). The single-photon optomechanical coupling rate is $g_0/2\pi \approx 25$ kHz, corresponding to a bare cooperativity of $C = 0.52$ that increases to $C_{\text{eff}} = 83$ with reservoir tuning, enhancing sensitivity more than two orders of magnitude. Phase-control measurements demonstrated dynamic manipulation of stored signals, with induced phase shifts $\Delta\phi > 2\pi$ using reservoir ramp pulses, confirming precise control of event detection with minimal nonlinear absorption and thermal interference.
2. **Memory reset:** The multiple resonant modes of a diamond microdisk provide a platform for memory-holding structures where information can be processed and altered via dynamic reservoir engineering. Pulse storage measurements showed an increase in storage lifetime from 1.1 μs to 7.7 μs with reservoir tuning, while the measured time–bandwidth product was 1.38, consistent with OMIT-based memories.
3. **Power efficiency:** The utilization of micro-scale structures, in addition to the reliance on the highly efficient coupling between the mechanical and optical resonant modes of the diamond microdisk, and incoming light signals, contributes to the superior power efficiency attributed to cavity optomechanical systems.
4. **Data transfer:** This work does not present any methodology for data transfer of optomechanical systems. Data manipulation is done on-device with no need for memory to be transferred to a processing unit.
5. **Material integrability:** By integrating the dynamic reservoir manipulator with the resonant diamond microdisk, this system offers a compact solution that enables memory-holding in addition to signal processing of incoming optical stimuli.

Table 4
Summary of classification scores and main characteristics for each evaluation metric (Luo et al. [51]).

Metric	Main Characteristics	Score (0–2)
Measurement	Durable and stable after 20,000 cycles; 0.05 V at 0% NaCl to 0.11 V at 50% NaCl, confirming an enhanced signal output due to NaCl integration; high spatiotemporal resolution; multimodal sensing for intelligent monitoring.	2
Memory reset	Continuous measurement capability; no explicit reset or memory-holding mechanism reported.	0
Power efficiency	Sensing current on the order of 10–40 nA under a resistance range of $\sim 10^3$ – $10^9 \Omega$, with an instantaneous peak power of 442.4 nW achieved at a resistance of 0.5 G Ω , confirming efficient energy transfer with minimal losses.	2
Data transfer	Wireless RF transceiver enables real-time communication, monitoring, and analysis with no explicit mention of novel technology	1
Material integrability	Scalable fabrication; integration of pressure and material sensing; Material tunability achieved by varying NaCl content, with decrease with less NaCl integration, from 0.08 MPa at 50% NaCl to 0.04 MPa at 0% NaCl, enabling a trade-off between durability and sensitivity.	2

Table 5
Summary of classification scores and main characteristics for each evaluation metric (Lake et al. [53]).

Metric	Main Characteristics	Score (0–2)
Measurement	Diamond microdisks couple optical ($\omega_o/2\pi = 197$ THz, $\kappa_o/2\pi = 0.856$ GHz) and mechanical ($\omega_b/2\pi \approx 2.14$ GHz, $\Gamma_b/2\pi = 190$ kHz) modes via radiation pressure. The single-photon coupling rate $g_0/2\pi \approx 25$ kHz yields a cooperativity increase from $C = 0.52$ to $C_{\text{eff}} = 83$ with reservoir tuning. Phase-control measurements demonstrated dynamic shifts $\Delta\phi > 2\pi$, enabling precise event detection with minimal absorption and heating.	2
Memory reset	Multiple resonant modes provide a memory-holding structure; information can be processed and altered via dynamic reservoir engineering. Pulse storage lifetime increased from 1.1 μs to 7.7 μs with reservoir tuning, and the measured time–bandwidth product was 1.38, projecting memory storage times up to ~ 5 ms.	2
Power efficiency	Efficient coupling of mechanical and optical resonant modes in micro-scale structures yields high power efficiency.	1
Data transfer	No external data transfer is addressed in this work; data is manipulated directly on-device.	0
Material integrability	Compact integration of dynamic reservoir manipulator with resonant diamond microdisks enables on-device memory and signal processing.	1

3.6. Non-electronic data storage via soft robotic non-volatile memory

Nemitz et al. [54] present a non-electric memory device for soft robots featuring both volatile and non-volatile memory for storing binary information. The non-volatile memory device comprises an elastomeric cylinder containing a bistable membrane and two tubes. Utilizing the function of a set and reset (S-R) latch constructed from three soft valves, the membrane can be flipped by applying pressure to the corresponding pressure chambers, enabling the permanent storage of information. The non-volatile memory device includes an array of pixels, each consisting of a pressure chamber, a membrane layer, a slit layer, and a display chamber. When the pressure chamber is pressurized, the membrane expands and pushes through the slit layer into the display chamber, while it retracts, and the slit layers cover the membrane layer when the display pixel is unpressurized. Experimental tests validate all combinations of information storage for two memory devices using a pressure manifold with four individual switches that output control pressure when actuated and atmospheric pressure when not actuated. Fig. 9 assigns a total score of 7 across the five evaluation metrics for the work by the authors on this non-electric memory device for soft robots, while Table 6 details the rationale behind the scoring.

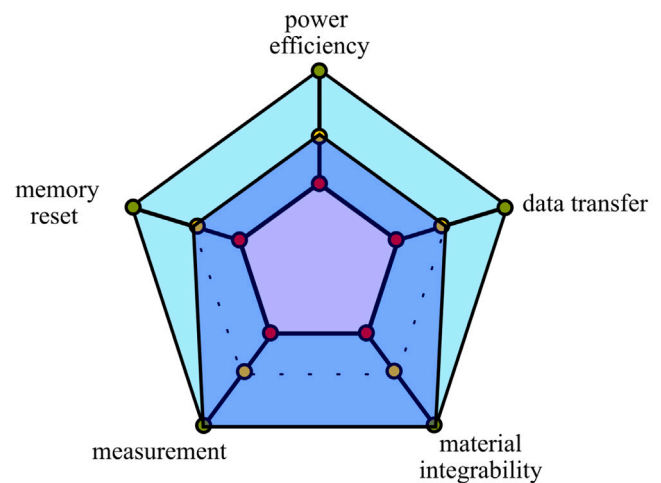


Fig. 9. Score chart of “Soft Non-volatile Memory for Non-Electronic Information Storage in Soft Robots” for the five considered evaluation metrics.

- 1. Measurement (sensitivity and event detection):** Binary information storage; minimum actuator pressure: 8 kPa. This device is capable of storing binary information, requiring a pressure of 8 kPa to move the membrane from the bottom to the top position. While only 8 kPa is necessary to write (and 1 kPa to erase) information from the memory, the device operates effectively at pressures up to 45 kPa.
- 2. Memory reset:** Control signals are directly linked to the membrane chambers inside the device, facilitating the flipping of the

membrane in either direction. The signals “S” and “R”, representing “SET” and “RESET”, respectively, enable the writing and erasing of information within the memory device.

- 3. Power efficiency:** The device employs a bistable membrane to enable the permanent storage of binary information in soft materials. It does not require electric power but relies on air pressure for writing and erasing information from the memory.
- 4. Data transfer:** Non-volatile memory retains data when powered off, whereas volatile memory loses data. Both memory types

Table 6
Summary of classification scores and main characteristics for each evaluation metric (Nemitz et al. [54]).

Metric	Main Characteristics	Score (0–2)
Measurement	Stores binary information via bistable membrane; requires 8 kPa to set and 1 kPa to erase; operates up to 45 kPa.	2
Memory reset	Controlled by direct pressure signals (SET/RESET), enabling reversible writing and erasing.	1
Power efficiency	No electricity required; relies on pneumatic pressure for operation.	1
Data transfer	Uses volatile and non-volatile memory for temporary and permanent storage; retains data when powered off.	1
Material integrability	Fully compliant material-based device, integrable into soft robots for storing sensor or system data.	2

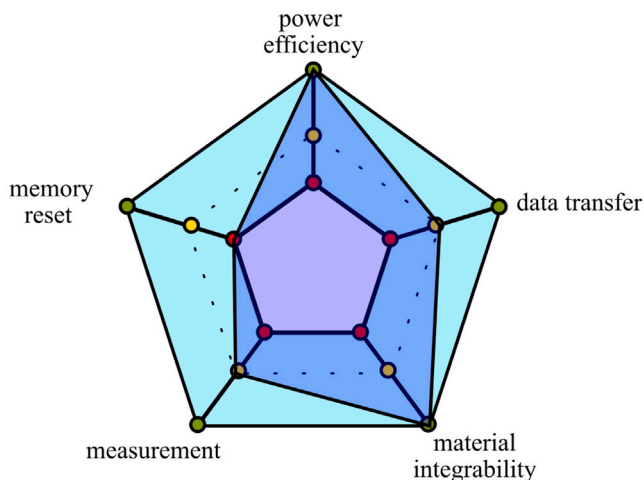


Fig. 10. Score chart of “Wireless Power Transfer and Energy Harvesting in Distributed Sensor Networks: Survey, Opportunities, and Challenges” for the five considered evaluation metrics.

are utilized for data storage; read-only memory typically represents non-volatile memory, while volatile memory, such as Random Access Memory, is used for temporary data storage in applications like word processors.

- Material integrability:** The device demonstrates the feasibility of material-based memory configured as a non-volatile memory device for storing information, such as sensor-generated data or internal system information. It can be seamlessly integrated into soft robots using entirely compliant materials.

3.7. Energy harvesting and wireless power transfer for distributed sensor networks

Ijamaru et al. [71] review advancements in wireless power transfer and energy harvesting technologies aimed at overcoming energy constraints in distributed sensor networks. They demonstrate a radio frequency-based energy harvesting technique, focusing on its design and performance in dense sensor networks where short distances improve power transfer efficiency. The study evaluates existing technologies, detailing their applications, limitations, and challenges, and provides a comparative analysis of wireless power transfer methods for the Internet of Things and sensor network scenarios. Practical insights into real-time applications of advanced power harvesters are presented, emphasizing their impact on enhancing sensor network performance. Fig. 10 presents a total score of 6 over the five evaluation metrics for the work by the authors on advances in wireless power transfer, while Table 7 details the rationale behind the scoring.

- Measurement (sensitivity and event detection):** The Power-cast power harvester receivers are radio frequency-based energy

harvesting devices that convert radio frequency electromagnetic radiation into direct current. The converted charge is stored in capacitors, providing power to micro-power devices. Supply power is automatically disabled when the charging threshold is attained.

- Memory reset:** No reset ability has been mentioned in this paper, and the sensor is without a self-memory system.
- Power efficiency:** The power consumption depends on the wireless power transfer technologies used in the application. Powercast RF harvesters demonstrate RF-to-DC efficiencies up to 80% across 10 MHz–6 GHz. The P1110 outputs up to 4.2 V for RF inputs of –6 dBm to +20 dBm, while the P2110 provides 5.5 V operation from inputs as low as –12 dBm. The TX91501 transmitter operates at 915 MHz with 3 W EIRP and 60° beamwidth.
- Data transfer:** The sensors are designed to receive energy exclusively from the N chargers. The model operates in two distinct phases. First, an exploration charging stage, secondly, an energy replenishment and data transmission phase. The power transmitter used in this work is an RF-based system specifically designed to deliver both data and power to energy receivers equipped with energy harvesters.
- Material integrability:** The targeted application of the wireless power transfer technology is standalone dense sensor networks, enabling deployment in remote locations without hardwired power lines. Near-field inductive coupling achieves up to 95% efficiency at short ranges but is impractical for large networks; magnetic resonant coupling demonstrates ~40% efficiency powering a 60 W bulb at 2 m; far-field RF transfer supports multiple receivers but drops to ~1.5% efficiency at 30 cm.

3.8. RFID-based passive temperature-sensing technology

Zhu et al. [62] propose a different concept of passive digital sensing to eliminate the need for a power supply. Unlike the semiconductor-based electrical digital sensing method, this approach is inspired by the absolute rotary encoders, and a non-electric analog-to-digital converter is designed to initially convert the parameter to be measured into a mechanical signal. This mechanical signal is then encoded into multiple digital bits by a passive digitizer, with each bit represented as an open or short state that can be detected by general IO ports. To illustrate this sensing concept, a passive RFID temperature sensor is developed using a bimetallic coil as the temperature sensing unit, where the digitized angular position of the coil is read and transmitted by a passive RFID tag to be completely passive. The proposed passive digital sensing principle demonstrated the potential to develop sensing technologies applicable to life-cycle zero-power sensing. Fig. 11 presents a total score of 7 over the five evaluation metrics for the work by the authors on passive digital sensing using RFID, while Table 8 details the rationale behind the scoring.

- Measurement (sensitivity and event detection):** A non-electric analog-to-digital converter, derived from absolute rotary encoders, is designed to digitize the rotation of the bimetallic

Table 7
Evaluation of the work “Wireless power transfer and energy harvesting in distributed sensor networks: Survey, opportunities, and challenges” (Ijmaru et al. [71]) within the framework of life-cycle zero-power sensing.

Metric	Main Characteristics	Score (0–2)
Measurement	RF-based harvesters convert electromagnetic radiation into DC; power stored in capacitors; supply disabled at charge threshold.	1
Memory reset ability	No reset mechanism or memory system reported.	0
Power efficiency	Dependent on technology; generally high consumption for wireless data transfer. RF harvesters achieve up to 80% RF-to-DC efficiency across 10 MHz–6 GHz. Produce a voltage of 4.2 V for –6 dBm to +20 dBm RF input, and 5.5 V from inputs as low as –12 dBm.	2
Data transfer	Operates in two phases: charging and energy/data transmission; RF transmitters deliver both data and power.	1
Material integrability	Designed for dense, standalone sensor networks in remote areas without wired power. Near-field inductive coupling achieves 95% efficiency; magnetic resonant coupling shows ~40% at a 2-meter range; far-field RF transfer supports multiple receivers but drops to ~1.5% efficiency at 30 cm.	2

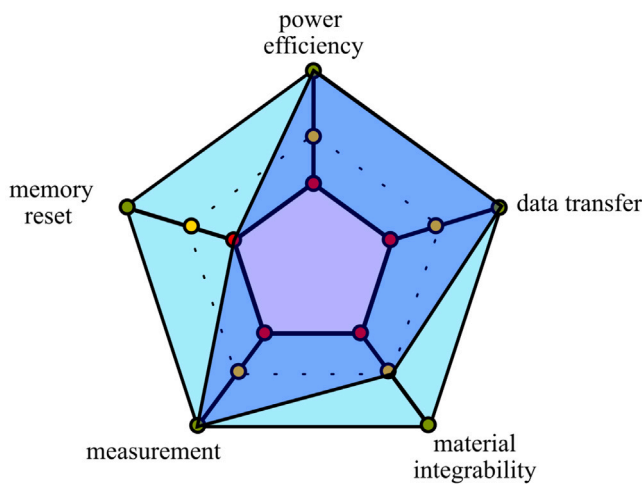


Fig. 11. Score chart of “Passive Digital Sensing Method and Its Implementation on Passive RFID Temperature Sensors” for the five considered evaluation metrics.

coil. Since the sensing element is fully passive and digital, it requires no electric power for operation, eliminating the need for onboard signal conditioning or processing. The digitized angular position of the coil is read and transmitted using a passive RFID tag. Test results indicate the temperature sensor has a measurement sensitivity of 1.32 °C/bit and a working range of over 10 m.

- 2. Memory reset:** The bimetallic coil-based sensor is proposed for temperature measurement without incorporating a self-memory system, and no reset capability is addressed in this paper.
- 3. Power efficiency:** Inspired by absolute rotary encoders, a non-electric analog-to-digital converter is utilized to digitize the rotation of the bimetallic coil. The passive and digital nature of the sensing element eliminates the need for electric power, onboard signal conditioning, and processing. The digitized angular position of the coil is transmitted using a passive RFID tag, enabling operation without an active power source. Experimental results showed that the system operates stably with a storage capacitor of 100 μF, providing ~55 μJ per charge–release cycle, sustaining about 2.3 s of active operation. The RFID chip demonstrates sensitivity down to –17 dBm with energy harvesting, though efficiency decreases from 100% at –11 dBm input to about 2.5% at –17 dBm.
- 4. Data transfer:** A passive RFID platform is employed to read the 6-bit digital states and transmit them to an RFID reader as needed. To enhance sensitivity and extend the sensor node’s

working range, an energy harvester is integrated into the RFID platform.

- 5. Material integrability:** The sensing platform can be seamlessly integrated with existing structures; however, it may face limitations when applied to soft, flexible materials or delicate surfaces, potentially compromising their integrity or functionality.

3.9. Zero-power MEMS-based wake-up receiver for wireless sensing nodes

Cassella et al. [58] developed a passive wake-up receiver to minimize the amount of power dissipated by wireless sensing nodes communicating within complex miniaturized networks when operating in their idle state. A fully passive RF wake-up receiver is proposed using a solid-state envelope detector and a MEMS-based resonant cantilever switch. By utilizing MEMS-based cantilever switches, passive RF receivers regulate the power delivered to the sensors, which aids in extending battery life. With an envelope detector and smoothing capacitors, the resonating cantilever beam signal can be translated into a clean DC signal, effectively powering an integrated sensor. By effectively eliminating standby power consumption while maintaining high sensitivity and simplifying the system architecture, this wake-up receiver highlights its potential for creating more efficient and sustainable wireless communication networks with an “Asleep-yet-Aware” mode, especially in environments with stringent energy constraints. Fig. 12 presents a total score of 6 over the five evaluation metrics for the work by the authors on passive wake-up receivers, while Table 9 details the rationale behind the scoring.

- 1. Measurement (sensitivity and event detection):** Wireless switching sensitivity of the MEMS-based resonator has been demonstrated to be as low as –60 dBm at a frequency of 750 MHz, which enables the interrogation of sensing nodes using low-power wireless interrogators currently used in “Asleep-yet-Aware” systems.
- 2. Memory reset:** Using the mechanical equilibrium of a MEMS-based cantilever beam, the system is shown to be resettable once the excitation RF frequency is stopped. This effectively uses the mechanical property of the structure to return to its original state without the need to consume any additional power. The MEMS resonant switch operates at 75.3 kHz with a quality factor of 4700, a gate–source gap of 600 nm, and a drain–source gap of 300 nm, ensuring reliable mechanical reset behavior.
- 3. Power efficiency:** Using a MEMS cantilever switch with minimum switching voltage not only eliminates sensor standby power consumption but also requires minimum switching power while interrogating the sensor. By applying a biasing voltage to the gate of a solid-state envelope detector, a wakeup receiver is realized.

Table 8
Evaluation of the work “Passive digital sensing method and its implementation on passive RFID temperature sensors” (Zhu et al. [62]) within the framework of life-cycle zero-power sensing.

Metric	Main Characteristics	Score (0–2)
Measurement	Passive non-electric ADC digitizes coil rotation; fully digital sensing with 1.32 °C/bit sensitivity and >10 m range.	2
Memory reset ability	No memory or reset function implemented.	0
Power efficiency	Operates without active power; passive RFID tag transmits data, avoiding onboard conditioning or processing. A 100 μF capacitor stores ~55 μJ per cycle (2.3 s operation), with turn-on/off at 2.64/2.42 V. RFID sensitivity improves to -17 dBm, though efficiency drops to ~2.5% at that level.	2
Data transfer	6-bit digital states read and transmitted via passive RFID; energy harvester enhances sensitivity and range.	2
Material integrability	Integrable into rigid structures; limited applicability to flexible or delicate materials.	1

Table 9
Evaluation of the work “750 MHz zero-power MEMS-based wake-up receiver with -60 dBm sensitivity” (Cassella et al. [58]) within the framework of life-cycle zero-power sensing.

Metric	Main Characteristics	Score (0–2)
Measurement	Sensitivity down to -60 dBm at a frequency of 750 MHz, enabling low-power wireless interrogation.	2
Memory reset	Switch operates at 75.3 kHz with reset achieved via MEMS cantilever returning to equilibrium once RF excitation stops.	2
Power efficiency	Eliminates standby power; MEMS switch minimizes switching power, and biasing enables wake-up operation.	1
Data transfer	no explicit mention of data transfer in this work	0
Material integrability	Simple architecture and MEMS resonance properties enable compact, long-term, integrable solutions.	1

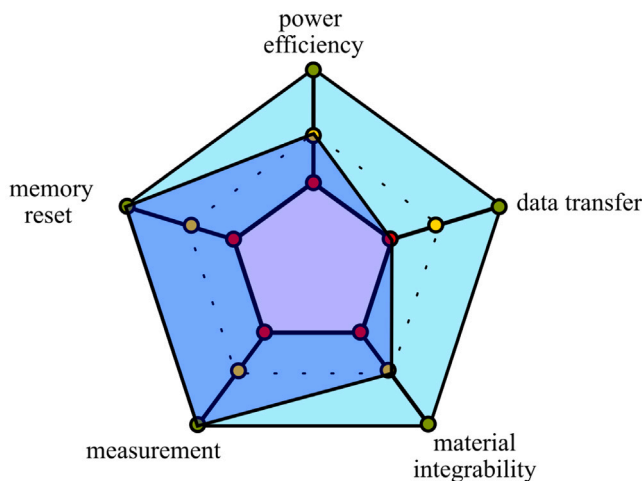


Fig. 12. Score chart of “750 MHz Zero-power MEMS-based Wake-up Receiver with -60 dBm Sensitivity” for the five considered evaluation metrics.

- Data transfer:** A MEMS-based cantilever switch configured as a wakeup receiver can be integrated using a simple resonance interrogator, which initiates measurement by powering up the sensing node itself. No data transfer information explicitly discussed in this work.
- Material integrability:** With the high simplicity of the circuit and the well-defined resonance behavior of MEMS cantilever structures, this technology offers a highly integrated solution to long-term standalone sensing.

3.10. Scoring of existing technologies

Table 10 reports the summation of the 9 technologies scored in this work, following the framework presented in Fig. 13. The right-hand side of Table 10 amalgamates the fusion of scores across the various technologies assessed, culminating in an overall score for each.

It is crucial to note that the authors do not assert the existence of a true life-cycle zero-power sensor within the current technological landscape. The objective of grading, rather than ranking, these technologies is to explore the theoretical and practical aspects that would constitute such sensors, especially within the domain of structural SHM. This exercise serves to identify key technological gaps and establish a benchmark for future innovations that may bridge the current limitations.

By assessing the capabilities of these sensing technologies through the structured framework presented in this paper, the authors aim to spark further research and development toward realizing life-cycle zero-power sensors. The authors intentionally avoided a comparison between the nine technologies, as they were not intended to be ranked, but were selected to highlight desirable features and illustrate the concept of a sensor capable of operating over the entire life-cycle of a structure.

Measurement (Sensitivity and event detection)

Across the nine technologies, measurement performance spans high-precision analog sensing, fully passive digital detection, and computation-aware arrays. The flexible Ni-NiO-Ni thermistor developed by Shin et al. [66] exhibits a rapid temperature response of 50 ms with high sensitivity of $-9.2\% \text{ } ^\circ\text{C}^{-1}$ at 25 °C and a linear range of 25 to 70 °C, which supports dynamic thermal event detection in thin substrates. The bioinspired triboelectric soft array proposed by Luo et al. [51] provides durable, multimodal contact sensing with enhanced voltage output that increases from about 0.05 V to 0.11 V as NaCl content rises, while maintaining stability over 20,000 cycles, enabling robust spatiotemporal event maps for touch and object interactions. Lake et al. [53] demonstrate optomechanical event detection using diamond microdisks in which optical and mechanical modes couple to yield a large cooperativity boost and precise phase control with induced shifts $\Delta\phi > 2\pi$, thereby enabling sensitive optical write and read of transient signals. In-sensor computing, as presented by Wan et al. [69], shifts part of detection from downstream processors to the sensor plane, supporting low latency and energy efficient detection at device and array levels. For chemical analytes, polysaccharide optical sensors reported by Azeman et al. [70] achieve low detection limits, for example Hg^{2+} at 0.275 nM, supported by plasmonic and fluorescence transduction strategies that permit selective, low-level event identification. Pneumatic soft memory devices designed by Nemitz et al. [54] act as binary

Table 10
Classification scores of selected sensing technologies within the framework of life-cycle zero-power sensing.

ID	Sensing technology	Total score (0–10)
1	High-Sensitivity Wearable Temperature Sensor Enabled by Monolithic Integration [66]	8
2	In-sensor Computing Through Materials and Device Integration [69]	6
3	Polysaccharide-Based Optical Sensors for Metal Ion Detection [70]	4
4	Integrating Machine Learning with Bio-Inspired Soft Sensor Arrays [51]	7
5	Optically Tunable Mechanical Memory for Light Processing [53]	6
6	Non-Electronic Data Storage via Soft Robotic Non-Volatile Memory [54]	7
7	Energy Harvesting and Wireless Power Transfer for Distributed Sensor Networks [71]	6
8	RFID-based passive temperature-sensing technology [62]	7
9	Zero-power MEMS-based Wake-up Receiver [58]	6

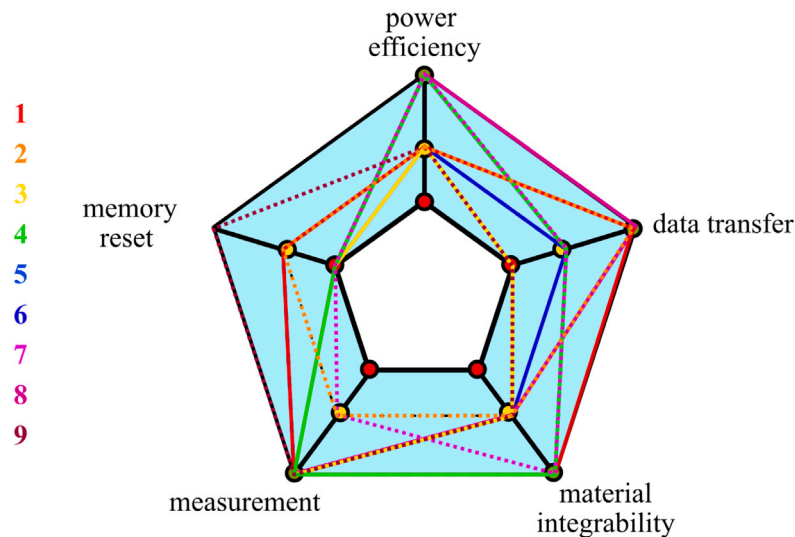


Fig. 13. Life-cycle zero-power sensor technologies score chart for the five evaluation metrics considered.

event detectors with a write threshold near 8 kPa, providing discrete state capture for pressure-mediated events. Zhu et al. [62] implement passive digital temperature sensing that encodes the angular position of a bimetallic coil into bits, achieving 1.32 °C per bit and a working read range beyond 10 m, which enables discrete thermal event quantization without local power. In distributed power harvesting, Ijamaru et al. [71] describe RF harvesters that convert incident fields to DC with supervisory cutoff at charge thresholds, yielding event-responsive charging behavior relevant to power-aware sensing nodes. Finally, Cassella et al. [58] report a MEMS wake up receiver with wireless switching sensitivity as low as −60 dBm at hundreds of kilohertz to low megahertz, which supports interrogation of passive nodes at low incident field strengths and extends detection to micro-scale resonant elements [58].

Memory reset ability

Memory behavior among the nine technologies ranges from single-use passive states to fully reconfigurable memory elements. The soft robotic pneumatic memory designed by Nemitz et al. [54] exemplifies mechanical storage, where bistable membranes physically store binary information and can be reset using direct pneumatic pressure signals for both SET and RESET states. Similarly, Lake et al. [53] employ optomechanical cavities that preserve optical states for approximately 7.7 μs and can be dynamically erased or rewritten through precise tuning of the optical reservoir, providing a reversible photonic memory mechanism. In contrast, Wan et al. [69] incorporate implicit memory through continuous data streaming in in-sensor computing arrays, where previous data are overwritten as new stimuli are processed, enabling adaptive temporal integration without dedicated memory hardware. Shin et al. [66] and Luo et al. [51] both offer quasi-resettable sensing functions, as their resistive and triboelectric responses return to

baseline conditions once external stimuli are removed, although they lack capacity for historical state retention. Zhu et al. [62], Azeman et al. [70], and Ijamaru et al. [71] do not feature intrinsic memory elements, as their systems rely on instantaneous signal transduction or power-dependent readout without persistent data storage. Finally, Cassella et al. [58] present a MEMS wake-up receiver that, while fully passive and power-efficient, also lacks integrated memory, though it could function as an interface to external non-volatile components in future designs. Among all technologies, only the pneumatic soft memory and the optomechanical cavity system exhibit active, reversible memory behavior without electrical power, indicating key pathways for advancing zero-power data persistence.

Power efficiency

Energy autonomy remains a defining objective across all nine sensing technologies. The MEMS wake-up receiver developed by Cassella et al. [58] establishes the benchmark for ultra-low-power operation, functioning entirely passively in standby while achieving wireless switching sensitivity as low as −60 dBm with no quiescent current draw. Similarly, Zhu et al. [62] present a passive RFID temperature sensor that consumes negligible power by relying on harvested radio frequency energy, storing charge in a 100 μF capacitor to sustain approximately two seconds of active operation per cycle. Ijamaru et al. [71] expand this principle into distributed wireless power-transfer networks, achieving 80 percent RF-to-DC conversion efficiency and 5.5 V output from input levels near −12 dBm, demonstrating how large-scale harvesters can extend operational lifetimes for sensor networks. Luo et al. [51] achieve instantaneous power generation of 442 nW through triboelectric conversion, providing continuous energy output during mechanical contact events. Shin et al. [66] maintain

microampere-level current consumption within the mega-ohm resistance range, ensuring minimal self-heating and stable thermal operation. The in-sensor computing architecture by Wan et al. [69] minimizes energy requirements by embedding computation within the sensing layer, significantly reducing data transfer and processing loads. Lake et al. [53] demonstrate efficient optical-mechanical coupling that operates through photon-phonon interactions at micro-scale energy levels, enabling event detection and memory without continuous power supply. Nemitz et al. [54] replace electrical actuation with pneumatic energy, allowing write and erase operations without electronic power. Finally, Azeman et al. [70] achieve effective sensing through optical excitation alone, entirely eliminating electrical power consumption. Collectively, these examples confirm that near-zero-power operation can be achieved across mechanical, optical, and electromagnetic domains, with hybrid energy-harvesting architectures emerging as essential enablers for long-term autonomous structural health monitoring.

Data transfer

The nine sensor technologies employ diverse strategies to transmit information while maintaining minimal energy consumption. Zhu et al. [62] and Cassella et al. [58] both utilize radio frequency communication methods, the former through passive RFID encoding and the latter through MEMS-based wake-up receivers that eliminate idle-state power draw. Ijamaru et al. [71] extend this approach to large-scale wireless power and data transfer frameworks, integrating simultaneous energy and information exchange for distributed sensor networks. Luo et al. [51] employ conventional RF transmission within their triboelectric arrays to support continuous, real-time data reporting. Shin et al. [66] rely on hardwired analog signal outputs, which, although less scalable, provide stable and accurate measurements suitable for laboratory-level structural health monitoring tests. Wan et al. [69] emphasize computational efficiency by embedding in-sensor data processing, which reduces the overall data transfer demand and associated power expenditure. Lake et al. [53] and Azeman et al. [70] represent optical and optomechanical approaches that focus on localized signal modulation or optical readout, removing the need for continuous electrical data transmission. Nemitz et al. [54] introduce a non-electronic alternative by encoding information within mechanical material states rather than transferring it externally. Collectively, these methods define a continuum between fully passive RF communication and computation-driven data compression, illustrating that the most sustainable transfer systems either harvest or eliminate transmission power entirely.

Material integrability

Structural compatibility and environmental resilience are essential for ensuring long-term operation of life-cycle zero-power sensing systems. The Ni–NiO–Ni flexible thermistor developed by Shin et al. [66] demonstrates excellent integrability through its 25 μm polyethylene terephthalate (PET) substrate and low-temperature laser annealing process, which yields a durable and flexible structure suitable for curved or layered applications. The porous silicone-based soft array created by Luo et al. [51] achieves tunable stiffness ranging from 0.04 to 0.08 MPa by adjusting NaCl content, allowing it to conform to complex geometries and maintain signal stability under repeated deformation. The polysaccharide optical sensors introduced by Azeman et al. [70] employ biodegradable materials such as chitosan and carrageenan, which offer environmental sustainability and chemical selectivity, although long-term stability remains limited due to moisture absorption and degradation. Nemitz et al. [54] advance material-embedded intelligence by integrating pneumatic non-volatile memory elements directly within soft elastomeric matrices, enabling compliant devices capable of mechanical information storage. Lake et al. [53] integrate diamond microdisks with optical reservoirs, producing compact mechanical-optical coupling structures that combine robustness with precision alignment.

Wan et al. [69] propose material-level integration of diverse transduction modalities, including magnetic, photonic, and chemical sensors, to achieve multifunctional and reconfigurable device networks. Ijamaru et al. [71] and Zhu et al. [62] design modular systems that support scalable deployment through rigid and semi-flexible mounting options, while Cassella et al. [58] demonstrate chip-scale MEMS integration suitable for embedding into hybrid sensor architectures. Collectively, these technologies highlight that material integrability, whether flexible, rigid, or embedded, remains central to realizing durable, maintenance-free, and fully autonomous sensing solutions capable of operating over the entire structural life cycle.

An ideal life-cycle zero-power sensor should (1) function durably over the structure's lifetime without planned maintenance, (2) require near-zero power to perform its sensing and data processing functions, and (3) maintain a memory state of the structure that allows on-demand access to historical information at any point in time. To the best of the authors' knowledge, no existing technology currently achieves true zero-power structural health monitoring across the full life cycle of a structure. Achieving this requires a combination of unconventional measurement methods to limit or eliminate sensing power requirements, reversible memory-holding techniques, passive or low-power sensor interrogation, and highly integrated sensing materials that resist deterioration while maintaining functionality across environmental and structural changes. True life-cycle zero-power operation thus emerges from the convergence of efficient energy harvesting, measurement transduction and transmission, and seamless material-device integration, ensuring sustained and autonomous operation throughout the entire structural life cycle.

4. Research needs and perspectives

The need for a true life-cycle zero-power sensing system for SHM applications is addressed in this work. Such systems are required to provide reliable data throughout the useful life of a structure, a capability that, to the authors' knowledge, is not currently demonstrated in the literature. To ensure effective selection, the objective evaluation of technologies is deemed paramount. A multi-metric classification framework is utilized to assess the life-cycle sensing capabilities of these systems. Attributes such as the ability to conduct measurements and retain and reset them with minimal intervention are identified as highly valuable. Additionally, power-efficient processing and data transfer are considered critical for the practical implementation of these technologies. Finally, material integration and the merging of the sensing system with the sensed medium are examined as essential metrics for achieving life-cycle zero-power sensing.

5. Conclusion

This work presented the first structured framework for evaluating life-cycle zero-power sensing technologies, motivated by the fact that no perfect life-cycle zero-power sensor currently exists. To address this gap, the framework formalizes a multi-metric evaluation system tailored to the needs of structural health monitoring (SHM). Five critical metrics: measurement sensitivity, memory reset ability, power efficiency, data transfer, and material integration were introduced and systematically applied to nine representative sensor technologies drawn from diverse fields, including MEMS, optomechanics, soft robotics, and passive RFID. Each metric was scored on a 0–2 scale, distinguishing between clear and measurable specifications, general statements, and no explicit information.

The main achievements of this work are twofold: (1) the introduction of a unified scalar-based methodology for quantifying life-cycle zero-power capability, built on five metrics identified as most significant to life-cycle zero-power sensing: measurement, memory reset ability, power efficiency, data transfer, and material integrability and

(2) the classification of existing sensor technologies within this framework using a scoring approach that distinguishes between cases where studies provide clear and measurable specifications of a metric (considered more relevant), general statements about a metric (considered relevant), or no explicit information at all (considered not relevant). This enables an objective and structured comparison of sensor technologies, ensuring that both qualitative descriptions and quantitative specifications can be incorporated into the unified scoring framework.

By offering both a structured evaluation framework and an interdisciplinary comparison of sensing modalities, this study lays the groundwork for advancing zero-power sensing technologies toward practical, life-cycle deployment in SHM applications.

CRedit authorship contribution statement

Joud N. Satme: Writing – review & editing, Writing – original draft. **Han Liu:** Writing – review & editing. **Pranav Agrawal:** Writing – review & editing. **Austin R.J. Downey:** Conceptualization. **Simon Laflamme:** Conceptualization. **Sriram Narasimhan:** Conceptualization.

Declaration of competing interest

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Data availability

No data was used for the research described in the article.

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