Towards Intelligent Materials: Smart Sensors and Iot for Adaptive Monitoring

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Abstract: - A combination of intelligent materials, smart sensors, the Internet of Things (IoT), edge computing, and artificial intelligence (AI) enables novel methods for material, structure, equipment, and engineered environment monitoring. Intelligent material systems can embed sensing functions and monitor the physical and environmental conditions continuously, unlike typical materials and monitoring systems which are based mainly on periodic checking and external instrumentation. In this narrative review, the authors explore the connection between smart sensing materials, IoT communication infrastructures, data analytics and adaptive monitoring. The review highlights the literature on smart sensor technologies, piezoelectric- and polymer-based sensing materials, structural health monitoring, IoT communication and edge intelligence, artificial intelligence of things, predictive monitoring, and environmental and industrial applications. The literature shows that the real added value for embedding smart materials with IoT is not a single architecture or performance, but rather the establishment of a continuous information flow between physical conditions and digital interpretation and, if required, decision support or actuation. There are various ways to see strain, vibration, temperature, pressure, deformation and other related variables with sensors that are embedded or attached to the surface such as piezoelectric materials, polymer-based sensors, MEMS devices, optical sensing technologies, etc. These sensing capabilities are expanded with wireless communications, gateways, edge processing, cloud services, and interoperable data environments, all part of IoT infrastructures. In addition to this, AI also aids in anomaly detection, prediction, classification and operational decision-making, but, as mentioned in the literature, many AIoT systems are still in a relatively early stage of implementation in the real world. Energy constraints, sensor drift, cyber security, data quality, interoperability, computational limitations and the ability to test adaptive systems under variable environmental and operational conditions are important challenges. The review ends that intelligent materials and IoT are not a validated technology but more a complementary element within an overall cyber-physical monitoring system. Future work should focus on easily tested sensing platforms, standardized testing protocols, easily understood analytics, efficient energy consumption, and field testing over extended periods of time.

Key-Words: - Intelligent Materials; Smart Sensors; Internet of Things; Adaptive Monitoring; Structural Health Monitoring; Artificial Intelligence of Things.

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1 Introduction

The monitoring and management of engineered systems are transforming because of the rapid growth of embedded computing, wireless communications technology, artificial intelligence, advanced materials, and cloud-edge infrastructures. The traditional materials typically have fixed structural, mechanical, electrical or thermal properties, and do not convey information about their condition. Monitoring is often done using external instruments, regular inspections, laboratory testing or by manual assessment. The appearance of intelligent materials and smart materials provides another option: to embed sensing, actuation, responsiveness, or other functional properties into materials or structures. These capabilities, when integrated with digital sensing and communication systems, can turn physical changes into an ongoing, observable process in an interconnected computational environment. The smart sensor is a key point of interaction between physical and virtual world. They incorporate sensing, electronic processing and, in increasing numbers, communication functions, making it possible to adjust the physical condition into digital information. Current smart sensor technologies are applicable to environmental monitoring, industrial automation, health care, transportation, infrastructure monitoring and other Internet of Things (IoT) applications. Brida et al. (2021) present the evolution of smart sensor technologies in the context of ever more connected wireless devices, and highlight the interdependence between sensing, communication, computing, and emerging IoT services. The Internet of Things (IoT) is an extension of individual sensor capabilities; it extends the capabilities of these distributed devices by linking them with each other via communication networks and computational services. The components of an IoT architecture can include sensor nodes, gateways, wireless networks, edge devices, cloud platforms, databases, dashboards, and analytic services. The communication and interoperability between the resource constrained devices and Internet services, using gateway principle, were studied earlier by Asensio et al. (2014). Their work shows that the IoT architectures are not only communication channels, but also mechanisms for connecting physical devices to other information infrastructures. The importance of this development is more obvious in the field of structural health monitoring and industrial condition monitoring. Continuous sensing can give information on strain, vibration, temperature, displacement, pressure, sound, changes in the system due to corrosion etc. As mentioned in the literature, wireless sensing and networked processing of data are gaining increasing interest as alternatives/complements to conventional monitoring arrangements (Bhatta & Dang, 2024; Rahita et al., 2024). Piezoelectric technologies provide direct material properties to sensing at the material level. Piezoelectric materials are able to respond to mechanical stresses with an electrical response and are thus suitable for use as sensing or actuation elements. Jiao et al. (2020) summarized the piezoelectric sensing methods for SHM such as impedance based methods, guided-wave and self-powered sensing methods. Thus through their review, they reveal that the utility of smart materials in monitoring and their physical sensing mechanism, installation arrangement, structural context, and interpretation of the resulting signals are not just dependent on the smart materials as such. Adding sensors, IoT and Artificial Intelligence adds another layer of functionality. Anomaly detection, operational state classification, prediction, and maintenance decision support are some areas where AI can be applied. The latest AI research on IoT has highlighted that the main functions that AIoT systems tackle are prediction, recognition and operation decision making. Meanwhile, the literature also warns of the lack of adequate testing of many AIoT systems in real operational environments (Khadam et al., 2025). With this background, this paper summarizes the convergence of intelligent materials, smart sensors, IoT and AI for adaptive monitoring. It is not to propose a new sensing architecture nor to make experimental claims. Instead, the paper draws on previous work, elucidates the functional connections between the technologies, outlines the key application areas and problems, and suggests potential future courses for empirically tested studies.

2 Conceptual Foundations of Intelligent Material Monitoring

2.1 Intelligent Materials and Smart Functionalities

The term intelligent materials refers to materials which have the ability to respond in useful ways to changes in their physical or environmental conditions. The answer could be the sensing, the actuation, mechanical response, electrical response or other response to the stimulus, depending on the material and application. The materials should not be considered as fully autonomous systems. A material can have a sensing ability without integrated computation, communication, prediction or autonomous control. It's worth noting that this distinction is important for an understanding of the relationship between materials and IoT. A piezoelectric material could generate an electrical response due to mechanical stress, but the material itself isn't necessarily used for network communication or artificial intelligence. The sensing signal has to be conditioned, acquired, transmitted, interpreted and, if necessary, linked to a decision process. As such, intelligent material monitoring can be perceived as a multi-layered interaction that involves material properties, sensing technology, computational systems, communication networks, and automated or human decision processes. This is well demonstrated in the literature for piezoelectric sensing. The application of Piezoelectric materials as sensors, actuators and sensing-actuation elements for structural health monitoring has been investigated. One of the reasons for their attractiveness is that they are able to directly interact with mechanical behavior of materials, and there is potential for embedding or integration with structural materials (Jiao et al., 2020). Another key group is the polymer-based sensing technologies. Harito et al. (2020) conducted a review on the smart polymer systems, such as conducting polymers, ionic gels, stimulus-responsive polymers, liquid-crystalline polymers and piezoelectric materials. Their review indicates the wide scope of the polymer based sensors, and the significance of the material parameters, sensor assembly and power integration in the realization of practical sensing system. The takeaway is it's only a piece of an intelligent monitoring puzzle. It is useful depending on the quality of the sensing mechanism, compatibility with the host structure or environment, stability of the signal, durability in the environment, energy consumption, data collection, communication and the interpretation of the data.

2.2 Smart Sensors as the Physical-Digital Interface

Smart sensors are the links between physical phenomena and computational systems. Typical sensors convert a physical parameter to a measurable parameter. The functionality of smart sensors is further enhanced by their local signal conditioning, processing, calibration, communication, or other types of embedded intelligence. Sensors can be used to measure temperature, humidity, pressure, vibration, acceleration, strain, displacement, acoustic emissions, chemical variables or electrical properties in the IoT applications. They are chosen based on the physical phenomenon of interest and the application's needs. In the case of a structural monitoring system, for instance, it may employ sensors to detect vibration or strain changes, while an environmental monitoring system might monitor humidity, gases, water chemistry, radiation, particulate matter or temperature. The proliferation of low-power wireless devices has opened the door to a wide distribution of sensors in space. Brida et al. (2021) recognize the following as interrelated elements in smart sensor development today: Wireless communication, computing ability, energy consumption, and sensing services. But new connectivity does not imply good monitoring. The accuracy of the sensor, its calibration, interference, data quality, power supply, communication reliability and maintenance of the device continue to be key issues. This means that the design of an intelligent monitoring system should start with the measurement problem instead of the decision of the popular communication or AI technology.

2.3 Internet of Things as the Communication and Integration Layer

The Internet of Things (IoT) offers ways for the distributed sensing devices to communicate with the computational platforms. Examples of components in an IoT environment can be sensor nodes, local gateways, wireless communication networks, edge processors, cloud services, storage systems, analytical applications, and user interfaces. Interoperability plays a crucial role in an IoT environment where devices may have varying computational power, data formats, communication protocols, and hardware specifications. Asensio et al. (2014) showed the contribution of gateways and middleware to establishing a connection between resource constrained devices and Internet based services. They make architecture's role as the interface between a plethora of physical devices and higher order digital services more apparent. The selection of the communication technology should, therefore, be based on the application requirements. Low-power wide area communications could be more appropriate for a distributed device with limited energy resources, while high bandwidth communications could be more appropriate in cases where large amounts of data need to be transferred. Depending on the range, bandwidth, and energy available, the latency needed, as well as network density, security, cost, and environmental conditions, the appropriate choice is to be made. Looking at the literature, it is clear that a requirement-driven approach to the interpretation of IoT is more appropriate, in which communication technologies are matched to the sensing tasks and operational constraints.

2.4 Adaptive Monitoring

Adaptive monitoring is a type of monitoring in which the information collected, processed, interpreted, and/or taken into action changes with changing conditions. Adaptation can be found at various levels. For the sensing level, sampling frequency can be adjusted based on the changes detected. On the communication level, the information or data passed from one sender to another could be altered to save energy or to deliver the most critical information. In the processing level, the computational resources can be distributed based on the significance of the received information. On the analytical level, models can classify changing patterns and/or identify deviations from expected behaviour. Operational level monitoring information can be used to assist in the maintenance or control decisions. These are not to be confused with autonomous material adaptation. An adaptive in an information processing sense monitoring system is not necessarily an adaptive in a mechanical sense of the physical material that's being monitored. Likewise, an AI system that suggests maintenance doesn't necessarily mean an AI system that carries out the corrective action. The distinction is key to prevent an over-ambitious description of “self-aware”, “self-healing” or “autonomous” materials.” These capabilities involve certain physical mechanisms, control pathways, validation procedures and safety assessments.

3 Smart Materials and Sensing Technologies for Adaptive Monitoring

3.1 Piezoelectric Materials

One of the most widely studied smart-material strategies for monitoring structures is piezoelectric sensing. The piezoelectric effect sets up a relationship between mechanical and electrical properties so that a mechanical change can be expressed by an electrical signal. Hence, piezoelectric material can be used to detect structural stress, strain, vibration, responses due to damage and other mechanical phenomena. According to Jiao et al. (2020), piezoelectric structural monitoring methods can be divided into four kinds: electromechanical impedance sensing, guided-wave technique, self-powered concept. The review also highlights the different sensing mechanisms, installation requirements, advantages, and limitations of each one. The chief opportunity for IoT-based monitoring is making the piezoelectric sensor and acquisition electronics and communication systems work together. This can convert localised material responses to digital data streams which can then be analysed. However, the attachment or embedding of a piezoelectric element does not make an IoT system. Power management, signal conditioning, wireless communication, calibration, data interpretation and environmental durability are all other issues that need to be dealt with.

3.2 Polymer-Based and Flexible Sensors

Flexible/wearable structures, conformability and lightweight construction are significant factors where polymer based sensors are important. Harito et al. 2020 list some types of smart polymers that are used in sensing, such as conducting polymers, ionic gels, stimulus-responsive polymers, liquid-crystalline polymers, and piezoelectric materials. This aspect makes them useful for adaptive monitoring as they could be embedded into surfaces, flexible structures, textiles and other areas where installing rigid sensors might be challenging. The actual performance of polymer sensors, however, is a function of material composition, sensor manufacturing, environmental exposure, mechanical loading of the sensor, electrical properties of the sensor and the stability of the material over time. For future polymer sensing systems in the field of IoT, attention should be paid to the durability, reproducibility, power consumption, signal conditioning, communication, and integration with computational platforms, along with sensitivity.

3.3 MEMS and Conventional Electronic Sensors

A further important basis for distributed monitoring is the microelectromechanical systems. Acceleration, vibration, pressure, temperature, and similar quantities can be measured in a compact form with a MEMS sensor. They are small and can be readily interfaced with electronics in embedded applications which makes them appealing for networked monitoring. In addition, the advancement of low-cost sensing platforms has led to a wide array of possible structural and environmental monitoring applications. Structural health monitoring in the modern era is reviewed and it is seen that MEMS plays an important role along with piezoelectric, fibre-optic, force, GPS, displacement and other sensor technologies as an important part of modern monitoring system (Sivasuriyan et al., 2024). Choosing the appropriate sensor should thus be dependent on the specific phenomenon to be measured, the resolution required, the environmental conditions, installation limitations, the power budget, the desired lifetime, and the requirements for data analysis, not on the notion that any one type of sensor is always superior.

3.4 Embedded and Surface-Mounted Sensing

Smart sensors can be placed in the material, attached to the surface of the material, or placed next to the structure being monitored. Close coupling between the sensor and the material response can be achieved via embedding, but may present fabrication, repair/replacement, calibration, and survivability problems. Sensors can be mounted on the surface to make installation and maintenance easier, but can also be vulnerable to damage from the environment or can introduce inaccuracies between the surface response and the internal condition of the material. There is, therefore, literature support for the context dependent approach. The location of the sensor should be based on the physical mechanism being measured, the anticipated damage or change, the ease of maintenance and the reliability requirements of the monitoring application.

4 Iot Architectures for Connected Monitoring

4.1 From Sensors to Networked Monitoring

The Internet of Things (IoT) is a technology that makes isolated sensing devices into connected monitoring systems. A conceptual description of the general monitoring pathway is:

Physical phenomenon → Sensor → Signal conditioning → Local/Edge processing → Communication network → Data platform → Analytics → Decision support and/or control.

This sequence is meant to be read as a theoretical composition, not as an actual architecture that the authors of this paper propose to experiment.

In the first stage, the physical signals are transformed into electrical or digital signals. The raw signals can then be transformed into more useful representations or noise can be removed by signal conditioning and preprocessing. Communication systems carry information to another place of computation. Edge processing can help to lower the amount of data that needs to be sent as raw data and cloud platforms can offer a scalable storage and a wider analytics. Where the computation should be placed is dependent on the application needs. Local computing or edge computing might be useful for time-sensitive applications while cloud computing could be useful for compute-intensive historical analysis. Hybrid solutions can thus be created that result in local responsiveness and central data management.

4.2 Communication and Interoperability

Mixed communication technologies are often used in IoT monitoring environments. It is determined by the range, energy availability, bandwidth, network topology, environmental conditions, security and requirements of the application. A key issue is that interoperability is important as different devices can support different protocols and data representations. Asensio et al. (2014) show how the concepts of gateways and middleware can serve as mediators between the energy constrained devices and Internet-based services. Thus, an intelligent monitoring system should not be characterised just by the fact that it has Wi-Fi or Zigbee or LoRaWAN or cellular communication or MQTT or any other protocol. A more significant question is whether the communication infrastructure can deliver reliable and secure information transmission that is suitable for the monitoring task.

4.3 Edge Computing and Distributed Intelligence

Edge computing brings certain compute functions near the data. This can decrease the amount of information sent to centralized platforms, and can help with faster interpretation locally. This is especially applicable in the case of sensor network systems producing continuous data or cases where abnormal conditions need to be detected as soon as possible. The research in AIoT has started to delve into the machine learning on edge devices, such as microcontrollers with limited resources. According to the study done by Trilles et al., (2024), numerous studies have been conducted on anomaly detection using AIoT, especially classification methods such as convolutional neural network (CNN) have been studied in edge-based anomaly detection. Another key constraint they review is the lack of computational power, as well as the need for analytical power to be balanced with constraints in embedded systems. This suggests that edge intelligence is promising, but is not necessarily faster, more accurate, or more reliable monitoring. The results are dependent on model complexity, hardware, quality of the data, deployment conditions, and model validation.

5 Artificial Intelligence for Adaptive Monitoring

5.1 Anomaly Detection

One of the most relevant uses of AI in the field of connected monitoring is anomaly detection. Machine learning models can learn patterns of normal or abnormal operating conditions, instead of being limited to fixed thresholds. In the case of intelligent materials and structures, the anomalies can be vibration, strain, temperature, acoustic activity, deformation, or another variable that can be measured. Anomalies in industrial environments can signify equipment degradation, abnormal operating conditions, or new equipment failures. The effectiveness of AI-driven anomaly detection relies significantly on the quality and representativeness of the training data. Models learned in a specific set of environmental conditions might not apply to different temperatures, loading conditions, sensor configurations, or operating conditions. The variability and uncertainty of the environment and operating conditions are crucial factors in AI-driven monitoring.

5.2 Predictive Monitoring

Predictive monitoring is to go beyond finding current abnormality and trying to estimate future system conditions. Degradation patterns can be modeled from the historical data of the sensor, the useful life of the sensor can be estimated, or conditions that are linked to potential future failures can be identified. IoT offers the data infrastructure needed for these kinds of applications and AI offers analytical mechanisms to identify the complex temporal relationships. But prediction is not a certainty. A predictive model gives an estimation under the assumption of the training data, features, assumptions and working conditions. This is further supported by the systematic review evidence that has been recently published. Khadam et al. (2025) identified AIoT research areas to include prediction, recognition and operational decision-making while also highlighting that many AIoT systems are still in early stages and lack of proper validation in a real environment.

5.3 Decision Support and Adaptive Control

The most integrated system is when the analysis results impact the actions of the operating unit. An AI system can suggest inspections, maintenance, sampling changes, and/or operating changes. For more sophisticated cyber-physical systems, this could involve linking analytics with actuators. The shift from prediction to self-control, however, will necessitate a considerable increase in the level of validation. Automated decisions can be impacted by false alarms, missed detection, model drift, communication failures, sensor failures and cyberattacks. For safety-critical systems, mechanisms to estimate uncertainty, to have human supervision, fail safe operation, and to be able to monitor the model are therefore needed.

The literature should thus be seen as a continuum:

Sensing – Monitoring – Anomaly detection – Prediction – Decision support – Automated control.

These stages don't need to be treated as a one-to-one ability to switch.

6 Applications of Smart Sensor and Iot-Enabled Monitoring

6.1 Structural Health Monitoring

Smart sensors and IoT are expected to have one of the most significant application areas in structural health monitoring. Combination of vibration, strain, displacement, temperature, acoustic and other sensing technologies can be used to monitor bridges, buildings, tunnels, pipelines, towers, and other infrastructure. According to Rahita et al. (2024), the last ten years of research on IoT in SHM was reviewed, and the trend of continuous, wireless and connected SHM is discussed. Bhatta and Dang also examined IoT applications in civil infrastructure, highlighting the need for real-time data from sensors and the management of information in the cloud. The smart materials offer another opportunity by bringing the sensing nearer to the actual physical source of structural change. For instance, a piezoelectric system can respond directly to mechanical responses; and MEMS or other sensors can deliver complementary measurements. So the value of IoT in this scenario is less about replacing wired sensors with wireless ones, and more about evaluating the impact of the wireless devices. It involves the generation of an information space that allows for the gathering and synchronisation of multiple measurements, analysis, visualisation and maintenance decisions.

6.2 Environmental Monitoring

Another big use case for IoT is environmental monitoring. Air and water quality, radiation, temperature, humidity, agricultural condition, and other environmental factors can be monitored by sensor networks. Ullo and Sinha (2020) studied smart monitoring systems in the environment, showcasing the use of IoT and recent sensing techniques to monitor various environmental parameters such as air quality, water quality, radiation and agriculture. One reason why networked environmental monitoring is valuable is because it distributes its space. Conventional monitoring stations are not the only way to obtain observations, but with connected sensors, they can actually get them from multiple locations. Distributed monitoring however comes with its own set of challenges, such as sensor calibration, heterogeneous environments, data quality, power availability, communication reliability and maintenance. Therefore, environmental IoT systems need to be tailored to the properties of the environment where they are deployed and the decision that the monitored data should be used for.

6.3 Industrial Monitoring and Predictive Maintenance

Industrial systems produce a variety of data, from machines, production lines, energy systems and equipment. Sensors are able to detect vibration, temperature, pressure, acoustic signals, electrical change and usage of energy. These data can be provided by IoT infrastructure for condition monitoring and maintenance analysis. The literature suggests the promise of IoT and AI to detect early signs of equipment problems and enable condition-based maintenance. But do not consider economics benefits as common outcomes. Actual savings will vary as a function of equipment, failure modes, sensor deployment, maintenance practices, data quality, model performance and organizational processes.

6.4 Smart Manufacturing

Smart manufacturing is the process of embedding sensing, networking, computation, automation and analytics into manufacturing environments. Smart sensors can provide data about machines and processes and IoT platforms can enable data integration and monitoring. AI can then be used for classification of operational states, anomaly detection, and prediction of equipment behaviour and process optimisation. One place where edge computing is relevant is when a quick local interpretation is required. However, in smart manufacturing environments, there are other factors to consider, as all machines, sensors, control systems, databases, and enterprise applications will have to work together. Implementing this requires an approach that ensures interoperability, cybersecurity, compatibility with legacy systems, data control and management, and ability to equip personnel. Interoperability, cyber security, compatibility with legacy equipment, data governance, and capability to equip personnel are, therefore, key implementation challenges.

7 Challenges and Limitations

7.1 Energy Constraints

Energy availability is still the most basic constraint for distributed IoT sensors. Numerous monitoring nodes are situated where frequent battery replacement of the nodes is challenging or costly. All functions of continuous sensing, wireless communications, computation and security require energy. Pereira et al. (2020) identify energy and communication as critical challenges for resource constrained IoT devices and provide an overview of the various approaches such as energy harvesting, wireless power transfer, backscatter communication and low power communication strategies. The energy challenge can be even more critical for embedded smart-material systems, where the sensors could be located in structures that are hard to access. These systems must then be designed to be energy-aware, adaptively sample the environment, and communicate at low power levels with, if possible, energy harvesting.

7.2 Sensor Drift and Data Quality

Stability of the measurement process is important for long-term monitoring. Sensors can drift, be sensitive to the environment, age, be contaminated, be mechanically damaged, or have installation changes. Predictive models can be especially sensitive to sensor drift as the AI system might "mistake" the degradation of the sensor as a change in the monitored material or equipment. Calibration and sensor-health monitoring thus need to be considered as components of an intelligent monitoring and not as maintenance functions. Data quality is a key consideration as well. Downstream analysis can be compromised by missing data, noise, synchronization issues, outlier data, communication issues, and inconsistent sensor behaviour.

7.3 Cybersecurity and Privacy

Having physical systems connected to networks brings cybersecurity issues. Com compromised sensors, gateways, communications or analytical platforms can allow unauthorized access, manipulation of data, denial of service, or disruption of operational processes. The security need of an intelligent material monitoring system thus goes beyond the traditional information security. A cyberattack can have an impact on not only confidentiality of data but integrity, and safety of a physical system. The security aspects should be taken into consideration as well as the restricted computational and energy capabilities of a large number of IoT devices. This poses an important design challenge with respect to the strength of the security, computational cost, energy usage, and responsiveness of the system.

7.4 Interoperability and Standardization

Different types of hardware devices and software platforms, communication protocols, and data formats are commonly used in heterogeneous devices. This can be complex to integrate, especially in the case of evolving systems. For scalable monitoring, the need for interoperability is therefore paramount. While communication can be achieved through gateway or middleware solutions, interoperability is also dependent on data models, semantic compatibility, standards, interfaces and governance.

7.5 AI Model Generalization

AI models can suffer from "real-life" differences in both the training environment and the deployment environment. Data from one structure, machine, climate, sensor arrangement or operating condition used to create a model may not be replicated in another location. This issue is important especially in the case of intelligent material monitoring, as the environment monitored may vary with time. Therefore, it is recommended that models be tested with realistic environmental and operational variability, and performance monitored after models are deployed. Systematic review evidence further suggested that most of the reported systems are still in a nascent stage of deployment, supporting the critical need for real-world validation of the recent AIoT literature.

7.6 Validation and Explainability

Reliability of a monitoring system should not be concluded from a high score from an AI model on a laboratory dataset. Representative data, suitable baselines, independent testing, environmental variability, sensor failure conditions and long-term deployments (when applicable) all are needed for meaningful validation. It is also important to provide explanations. Sometimes, engineers and maintenance people need to know why a system has determined a condition to be abnormal so that they can take action. Explainable AI can thus help interpret the information fed into the decision-making process by predictive models.

8 Integrated Discussion

The previous literature reviewed in this paper shows that intelligent monitoring of materials is more of an integration of complementary technologies instead of one device or architecture. Smart materials have physical sensing or stimulus-responsive properties. The physical conditions are transformed into usable signals by smart sensors. Communication and integration is the thing IoT offers. Edge and cloud computing resources are available to computational resources. Artificial intelligence is used in interpretation, prediction and decision making. This distinction directly tackles an important constraint of the previous version of the paper. The technologies mentioned in the literature are not a validation for a new architecture according to the present authors. Existing research publications show that certain sensor and material combinations, communication technologies and analytics have been explored in specific experimental and/or operational settings. It is therefore important that the findings are considered in the original contexts. The case of piezoelectric sensing is one that is instructive. Jiao et al. (2020) show that various sensing principles and structures have been explored for piezoelectric technologies. The review does not represent one universal piezoelectric monitoring architecture, but rather illustrates that there are various monitoring architectures and each has its own conditions and limitations. Likewise, the IoT-s literature has been shown to be informative about the benefits of connected sensing, but also highlights resource limitations, communication constraints, and interoperability issues. Smart sensing and IoT development requires simultaneous consideration of the communication, computing and energy requirements, along with requirements for sensing, as shown by Brida et al. (2021) and Pereira et al. (2020). The existing literature on structural health monitoring also suggests that IoT can be used to continuously collect and remotely access the structural data. Rahita et al. (2024) and Bhatta and Dang discuss the importance of wireless and connected technologies in structural monitoring.

AI adds another layer of capability, but needs to be nuanced. In the recent systematic review by Khadam et al. (2025), it is revealed that AIoT research areas include prediction, recognition, and decision making in operations and that many systems are still immature and not validated in the real world. This is significant as regards intelligent-material monitoring, as autonomy should be claimed only if it can be shown to work in realistic conditions.

The resulting conceptual relationship can therefore be represented as:

Intelligent material or physical system
↓
Smart sensing
↓
Signal acquisition and preprocessing
↓
IoT communication and interoperability
↓
Edge/cloud computing
↓
AI-enabled interpretation
↓
Monitoring, prediction and decision support
↓
Human or validated automated response

This framework is important because it conceptualizes the teaching and learning of a language instead of being an experiment. It offers a means of comprehending how all of the technologies outlined throughout the literature can transition, interact and co-exist without assuming that the authors have necessarily adopted or tested the entire sequence. Another implication has to do with “adaptive.” It can be in the sense, in the communication, in the computation, in the analysis or in the physical action. Further research should explicitly define the layer which adapts, what triggers the adaptation, what mechanism executes the adaptation and how the response is validated. This would help to avoid general statements regarding autonomous or self-healing systems when the underlying evidence is related to monitoring or prediction.

9 Research Gaps and Future Directions

Several research directions emerge from the literature. First and foremost, future research should create experimentally proven smart-material sensor systems instead of only theoretical frameworks. This study should describe the material, sensing method, manufacturing or integration process, instrumentation, sampling technique, communication technology, dataset, baseline, validation protocol, and testing circumstances.

Long-term field validation is secondly needed. Laboratory tests could not properly reflect temperature changes, humidity, vibration, mechanical stress, electromagnetic interference, sensor ageing, communication failure, or other ambient conditions met during deployment.

Thirdly, energy-aware sensing has to be given more thought. Intelligent material monitoring systems should look at adaptive sampling, energy harvesting, low-power communication, and local processing to let sensor nodes run for longer without often manual help.

Fourth, the monitoring system should include sensor health. A system ought to separate variations in the tracked material from those brought on by sensor malfunction or communication errors.

Fifth, artificial intelligence models ought to be judged under practical operational fluctuation. Future evaluation frameworks have cross-site validation, temporal validation, sensor-failure scenarios, environmental fluctuation, uncertainty assessment, and explainability.

Sixth, interoperability ought to be seen as a research issue instead of only an implementation element. Better integration across varied monitoring settings could be made possible by standardized data models, communication interfaces, device descriptions, and semantic representations.

Finally, smart monitoring systems have to set control apart from prediction. Safety-critical infrastructure needs more proof for automated intervention than anomaly detection or decision support. Before autonomous reactions are used, human monitoring, fail-safe systems, uncertainty assessment, cybersecurity, and regulatory aspects should thus be integrated.

10 Conclusion

Important technical path for creating more ongoing and data-driven monitoring systems is the confluence of intelligent materials, smart sensors, the Internet of Things, edge computing, and artificial intelligence. Though smart sensors offer mechanisms for converting physical data into digital information, the research shows that smart materials might have sensing or stimulus-responsive properties. Artificial intelligence can help with anomaly detection, prediction, categorization, and decision support; IoT adds these skills by linking dispersed devices to communication and computing systems. Still, the data examined does not support regarding these technologies as a single, universally accepted design. Various sensing materials, sensor layouts, communication technologies, computer setups, and artificial intelligence models handle various monitoring issues. Their functioning relies on environmental factors, data quality, energy availability, network qualities, and validation techniques as well as application environment. For structural health monitoring, piezoelectric, MEMS, optical, and other sensing devices offer complementary ways to see structural behavior. Distributed IoT sensors can help environmental monitoring provide ongoing observation across several physically varied sites. Connected sensors and artificial intelligence can help with predictive maintenance and condition monitoring in industrial settings. The biggest chance across these applications is the establishment of a continuous information channel between physical systems and digital decision-making processes.

The main restrictions are equally important. Energy limits, sensor drift, data quality, cybersecurity, interoperability, computational limits, model generalization, and inadequate real-world validation can stop potential lab ideas from turning into trustworthy working systems. Recent AIoT evaluations especially show that many smart connected devices are still in the somewhat early stages of practical validation. The next phase of study therefore ought to go from general claims of intelligent, autonomous, or self-healing systems toward meticulously defined and experimentally tested monitoring systems. Future research on integration processes, data sources, communication arrangements, analytical models, baselines, validation conditions, uncertainty, and constraints should specify the precise sensing materials and devices employed. Such openness will enable the sector to differentiate between theoretically possible, literature-reported performance, and scientifically proven capacity. Therefore, the combination of smart materials, smart sensors, IoT, and artificial intelligence offers a lot of potential, but its scientific worth will rely on strict data. A trustworthy path toward adaptive monitoring is found in the progressive linking of material-level sensing, dependable communication, strong analytics, and verified decision systems within well-defined application settings rather than in assigning borrowed performance data to a new design.

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