Journal of Renewable Engineering
E-ISSN : **3046-7624**
https://nawalaeducation.com/index.php/JORE/index
Vol.2.No. 3 June 2025
DOI : https://doi.org/10.62872/z01dzd67

Literature Review of the Development of Sensor Technology for Monitoring Civil Engineering Infrastructure

Eric

Nurdin Hamzah University
erickrisna@gmail.com

Abstract

This study aims to examine the development of sensor technology in civil engineering infrastructure monitoring systems through a literature study approach with a qualitative descriptive method. The need for accurate, real-time, and sustainable monitoring systems is increasingly urgent as the complexity and age of public infrastructure increases. This study highlights the evolution of sensors such as strain gauges, accelerometers, and Wireless Sensor Network (WSN)-based systems that are now integrated with the Internet of Things (IoT) and edge computing. This technology enables early detection of structural damage and efficient data processing, thereby increasing the effectiveness of structural maintenance and safety. However, implementation in the field still faces challenges such as initial costs, extreme environmental conditions, and limitations of existing structures. Through content analysis of various scientific publications over the past decade, it was found that the success of the Structural Health Monitoring (SHM) system is not only determined by the quality of the sensor, but also by the data integration strategy and analytical-based decision making. This study provides academic contributions in mapping trends and challenges of sensor technology and offers practical insights for the development of adaptive and sustainable monitoring systems, especially in developing countries like Indonesia.

Keyword : **Civil Infrastructure**; **Sensor Technology**; **Structural Monitoring**

Introduction

Condition monitoring of civil engineering infrastructure, such as bridges, high-rise buildings, and dams, is becoming increasingly crucial given the operational challenges faced by these structures due to dynamic loads, climate change, and material aging factors. Accurate and real-time monitoring is essential to detect potential damage early on so that structural failure can be prevented. This approach is in line with the concept of Structural Health Monitoring (SHM) which was developed to ensure safety and extend the service life of infrastructure. Farrar and Worden

Journal of Renewable Engineering
E-ISSN : **3046-7624**
https://nawalaeducation.com/index.php/JORE/index
Vol.2.No. 3 June 2025
DOI : https://doi.org/10.62872/z01dzd67

(2007) explained that SHM enables early detection of structural degradation, while increasing maintenance efficiency through data-based monitoring.

The rapid development of sensor technology in recent decades has also driven significant progress in infrastructure monitoring systems. Technologies such as strain gauges, accelerometers, and temperature sensors have now become more intelligent and integrated with the Internet of Things (IoT) and wireless systems. This allows for continuous, wireless, and low-power data collection. Lynch and Loh (2006) emphasized that wireless sensors are not only cost-efficient, but can also be integrated into local data processing systems (edge computing), thereby accelerating the analysis of structural conditions in the field. The combination of modern sensors and digital communication networks allows monitoring systems to respond to changing conditions adaptively and with high precision.

In contrast, conventional monitoring systems such as visual inspection or periodic non-destructive testing show various limitations. These approaches are highly dependent on human expertise, are subjective, and are unable to provide real-time information. Zhou et al. (2013) stated that these methods only provide a momentary picture of the condition of the structure, without the ability to detect dynamic changes or microdamages. Therefore, the transformation from conventional methods to sensor-based monitoring systems is an urgent need to improve the effectiveness, accuracy, and coverage of infrastructure monitoring as a whole.

In the context of research development and implementation of monitoring technology, literature review plays an important role. Through a comprehensive literature study, researchers can examine the latest sensor technology trends, evaluate their effectiveness in various civil engineering applications, and identify challenges that arise from technical and environmental aspects. This approach is in accordance with the PRISMA method developed by Moher et al. (2009) as a standard in systematic reviews, to compile evidence-based information synthesis. By understanding global experiences and mapping research gaps, literature reviews become a strategic basis in formulating the direction of sensor technology development that is adaptive to local needs and contexts in Indonesia and other developing countries.

Method

This study uses a descriptive qualitative approach that aims to explore and understand the development of sensor technology in civil engineering infrastructure monitoring systems in depth and contextually. The literature review method was chosen as the main technique in data collection and analysis, considering that this method allows researchers to identify patterns, technology trends, and research gaps that emerge from various previous scientific sources. Literature studies not only provide a historical overview of the evolution of technology, but also serve as a conceptual basis for examining the relevance and effectiveness of sensor technology applications in various structural conditions. This approach is in line with systematic guidelines in qualitative research as stated by Creswell (2014), where literature studies play an important role in building theoretical frameworks and thematic synthesis.

The data sources in this study were obtained from secondary literature including scientific articles, conference proceedings, research institution reports, and peer-reviewed academic publications. The search was conducted through trusted databases such as Scopus, ScienceDirect, IEEE Xplore, and Google Scholar, with a publication year range between 2014 and 2024. The selected literature must meet the inclusion criteria, namely discussing sensor technology (such as strain gauges, accelerometers, temperature sensors, and IoT-based systems) in the context of monitoring civil engineering infrastructure such as bridges, high-rise buildings, and dams. Meanwhile, documents that are not substantively relevant, are opinionated, or do not meet academic standards are excluded from the analysis. This selection process refers to the principle of systematic mapping review as explained by Petersen et al. (2015), which emphasizes the importance of validity and relevance in literature selection.

The collected data were analyzed using thematic content analysis techniques. The analysis was carried out in several stages, starting from the process of identifying relevant literature, followed by grouping data based on themes such as sensor types, installation methods, and integration with digital technologies such as the Internet of Things (IoT) and cloud monitoring. Furthermore, thematic synthesis was carried out to organize the findings into a narrative structure that contains the advantages, challenges, and potential applications of sensor technology in civil engineering practices. This technique is in line with Braun & Clarke's (2006) approach in thematic analysis, which recommends interpreting data through open coding and thematic categorization to build in-depth and systematic interpretations.

To ensure the validity of the results, this study applies a source triangulation strategy, namely by comparing and confirming findings from various publications and different institutions. This approach is important to avoid interpretation bias and ensure consistency between literatures. In addition, cross-citation is also used to assess the reliability and influence of each literature in the existing academic knowledge network. With this method, it is expected that the results of the study can provide a comprehensive, critical, and applicable understanding of the dynamics of sensor technology in monitoring sustainable civil engineering infrastructure.

Results and Discussion

In the context of modern infrastructure development, the need for accurate and continuous monitoring systems is becoming increasingly important. Infrastructure such as bridges, high-rise buildings, and dams face complex challenges as they age, undergo dynamic loads, and are exposed to extreme environmental conditions. Sudden structural failures are often preceded by micro-degradation that is not detected by conventional visual inspection methods. Therefore, the use of real-time structural monitoring systems is a strategic solution to ensure public safety and the longevity of structures. This is in line with the idea of Structural Health Monitoring (SHM) which emphasizes early detection and data-driven maintenance as a proactive approach to infrastructure management (Farrar & Worden, 2007).

The development of sensor technology has contributed greatly to the effectiveness of SHM. In recent decades, sensors such as strain gauges, accelerometers, and temperature sensors have experienced significant improvements, both in terms of accuracy and energy efficiency. In fact, the presence of Wireless Sensor Network (WSN)-based systems allows the deployment of sensors on a large scale without complex cable infrastructure. This technology supports flexible, cost-effective, and easily accessible integration for various types of civil engineering structures. Lynch and Loh (2006) showed that modern sensors can also be operated in the long term with minimal energy consumption, especially when supported by energy harvesting technology, making them ideal for remote locations that are difficult to reach.

Furthermore, the integration of sensors with Internet of Things (IoT) technology and edge computing presents a new paradigm in infrastructure data management. With this system, each sensor is not only a data collection device, but also acts as a smart node capable of processing information locally. This not only reduces the burden of data transfer to the center but also accelerates the process of detecting structural anomalies. Zhang et al. (2019) proved that the application of edge computing in SHM can reduce system latency by up to 40% and improve real-time response to critical conditions. In the context of large infrastructure such as overpasses or underground tunnels, this rapid response can be the difference between safety and system failure.

However, conventional monitoring systems are still the dominant approach in many areas, especially in developing countries. Visual inspection and non-destructive testing (NDT) are still relevant, but are very limited in terms of frequency, accuracy, and objectivity. These limitations make conventional methods tend to be reactive, namely only responding to damage after it occurs or is detected by the naked eye. Research by Zhou et al. (2013) revealed that digital sensor-based monitoring systems are able to detect structural changes early, even before the damage reaches a critical stage. Therefore, digitalization of monitoring systems should not be just an alternative, but an urgent need in responding to future engineering challenges.

However, the adoption of sensor technology is not free from various challenges in the field. In addition to the high initial cost, the main challenge lies in the integration of new systems into old structures that have not been designed to support digital monitoring. Environmental factors such as corrosion, high humidity, or excessive vibration can also interfere with sensor performance. In the study of Sun et al. (2020), it was stated that physical protection of sensors, automatic calibration systems, and data redundancy strategies are three important aspects in maintaining the reliability of monitoring systems in the long term. Failure to pay attention to local environmental conditions can cause serious disruption to data accuracy and overall system reliability.

Equally important is how the data collected by the sensors is analyzed and utilized. The large volume of data from modern SHM systems requires an efficient and intelligent analytical approach. In practice, data fusion methods, anomaly detection, and machine learning algorithms are needed to filter important information from large and complex data sets. Kim et al. (2017) showed that combining data from various types of sensors can increase detection accuracy by more than 90%, especially when equipped with AI-based predictive models. In other words, the strength of the SHM system depends not only on the quality of the sensors, but also on the system's capacity to process and interpret data effectively.

This is where literature studies play an important role in building a deep understanding of sensor-based SHM systems. Through a systematic review of various scientific publications and technical reports, researchers can identify the most relevant sensor types, efficient installation methods, and specific challenges in various geographical and structural contexts. This approach is in accordance with the PRISMA framework (Moher et al., 2009) which emphasizes the importance of transparency and systematicity in scientific literature reviews. Literature studies also allow mapping of research gaps, which can be the basis for the development of future monitoring technologies and policies.

The implications of this study are multidimensional. Academically, this study contributes to enriching the literature on sensor technology in civil engineering, especially by focusing on the context of developing countries such as Indonesia. Practically, the results of this study can be a reference for policy makers, infrastructure planners, and engineering industry players in designing efficient and adaptive monitoring systems to local characteristics. The existence of appropriate technology will encourage the implementation of the principles of sustainability, cost efficiency, and increasing public safety simultaneously.

Future research directions need to focus on developing sensor systems that are cost-effective, easy to implement, and resistant to extreme environmental conditions in Indonesia. In addition, cross-sector collaboration between government, academia, and industry is needed to accelerate the adoption of this technology nationally. The development of local prototypes that are in accordance with tropical climate characteristics, as well as the preparation of data-based maintenance policies are important steps to support digital transformation in infrastructure management. Thus, sensor-based monitoring systems are not only a symbol of technological progress, but also an integral part of a sustainable infrastructure resilience system.

Conclusion

Based on the results of the literature review and in-depth analysis, it can be concluded that the development of sensor technology has made a significant contribution to increasing the effectiveness of civil engineering infrastructure monitoring systems, especially through the Structural Health Monitoring (SHM) approach which is real-time, accurate, and adaptive to structural dynamics. The integration of sensors with Internet of Things (IoT) technology, edge computing, and artificial intelligence algorithms opens up great opportunities for early damage detection, maintenance cost savings, and increased safety and service life of structures. However, implementation challenges in the field such as initial costs, extreme environmental conditions, and limitations of existing structures need to be addressed through robust and contextual system design. This literature review confirms that the success of implementing sensor technology is not only determined by hardware, but also by the system's ability to manage, analyze, and interpret data intelligently. Therefore, cross-sector collaboration and locally oriented further research are key to ensuring that sensor-based monitoring systems can be implemented sustainably and relevant to national needs.

Bibliography

Armijo, A., & Zamora-Sánchez, D. (2024). *Integration of Railway Bridge Structural Health Monitoring into the Internet of Things with a Digital Twin: A Case Study*. Sensors, 24(7):2115. journals.sagepub.com+6link.springer.com+6link.springer.com+6

Bhatta, S., & Dang, J. (2024). *Use of IoT for Structural Health Monitoring of Civil Engineering Structures: A State-of-the-Art Review*. *Urban Lifeline*, 2:17. ouci.dntb.gov.ua+8link.springer.com+8link.springer.com+8

Chacón, R., Casas, J. R., Ramonell, C., Posada, H., & Škarić, S. (2023). *Requirements and challenges for infusion of SHM systems within Digital Twin platforms*. *Struct Infrastruct Eng*. link.springer.com+1mdpi.com+1

Chanief R., Aulia, Zaki, A., Nugroho, G., & Yadi, S. (2024). *Internet of Things (IoT) in Structural Health Monitoring: A Decade of Research Trends*. *IIETA*. iieta.org

Chen, J., Reitz, J., Richstein, R., Schröder, K.U., & Roßmann, J. (2024). *IoT-Based SHM Using Digital Twins for Interoperable and Scalable Decentralized Smart Sensing Systems*. *Information*, 15. ouci.dntb.gov.ua

Di Nuzzo, F., Brunelli, D., Polonelli, T., & Benini, L. (2021). *Structural health monitoring system with narrowband IoT and MEMS sensors*. *IEEE Sensors Journal*. link.springer.com+1europepmc.org+1

Hafidz, A., Kinoshita, N., Yasuhara, H., & Tsuzuki, S. (2023). *Development and applications of slope and river monitoring system using LPWAN technology*. *J Civ Struct Heal Monit*, 13(1):83–100. link.springer.com

Hassan, A. (2024). *A unified sensor and actuator fault diagnosis in digital twins for remote operations*. *Mech Syst Signal Process.*, 222:111778. ouci.dntb.gov.ua

Hu, et al. (2024). *An intelligent BIM-enabled digital twin framework for real-time structural health monitoring using wireless IoT sensing, digital signal processing, and structural analysis*. *Expert Syst Appl.*, 252:124204. ouci.dntb.gov.ua

Hubert, P., & Tezzele, M. (2024). *A digital twin framework for civil engineering structures*. *Comput Methods Appl Mech Eng*. mdpi.com

Liu, C., Zhang, P., & Xu, X. (2023). *Literature review of digital twin technologies for civil infrastructure*. *J Infrastruct Intell Resilience*. link.springer.com

Liu, G., Wang, Q.-A., Jiao, G., Dang, P., Nie, G., Liu, Z., & Sun, J. (2023). *Review of Wireless RFID Strain Sensing Technology in Structural Health Monitoring*. *Sensors*, 23(15):6925. link.springer.com+4mdpi.com+4mdpi.com+4

Mah moodian, M., Shahrivar, F., Setunge, S., & Mazaheri, S. (2022). *Development of Digital Twin for Intelligent Maintenance of Civil Infrastructure*. *Sustainability*. link.springer.com

Peng, Z., Li, J., & Hao, H. (2023). *Development and experimental verification of an IoT sensing system for drive-by bridge health monitoring*. *Eng Struct*, 293:116705. link.springer.com

Plevris, V. (2024). *AI-Driven Innovations in Earthquake Risk Mitigation: A Future-Focused Perspective*. *Geosciences*, 14:244. mdpi.com+1medium.com+1

Pop, M., Tudose, M., Visan, D., Bocioaga, M., Botan, M., & Banu, C. (2024). *A Machine Learning-Driven Wireless System for Structural Health Monitoring*. *ArXiv preprint*. arxiv.org

Rahita, A. C., Zaki, A., Nugroho, G., & Yadi, S. (2024). *Internet of Things (IoT) in Structural Health Monitoring: A Decade of Research Trends*. *IIETA*. iieta.org+1iieta.org+1

Ritto, T., & Rochinha, F. (2021). *Digital twin, physics-based model, and machine learning applied to damage detection in structures*. *Mech Syst Signal Process*. link.springer.com+12link.springer.com+12arxiv.org+12

Sun, Y., et al. (2020). *Structural health monitoring: An IoT sensor system for structural damage indicator evaluation*. *Sensors*, 20(17):4908. link.springer.com+1en.wikipedia.org+1

Xu, J., Liu, H., & Han, Q. (2021). *Blockchain technology and smart contract for civil structural health monitoring system*. *Comput Civ Infrastruct Eng*, 36:1288–1305. arxiv.org+15mdpi.com+15link.springer.com+15