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Role of Artificial Intelligence in Structural Health Monitoring: A Brief Evaluation

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Abstract

Artificial intelligence (AI) refers to the capacity of a machine or a computer to 'think' or reason in the way a human would, utilizing experience, learned facts, and flexible rules to solve problems that may not fit the standard outlines for a normal algorithm. From this follows the utilization of AI in various sectors, such as the information technology (IT) industry, media, healthcare and medicine, logistics, environmental sustainability, finance, business, and even judicial systems. Nowadays, the application of AI in the segment of engineering and materials science is also growing fast. Under this sector, AI can be implemented to replace trial-and-error lab work by predicting future models for the computational material discovery subsegment. In another subcategory of this segment, namely structural health and digital twins, AI can be applied for computer vision inspections for identifying cracks, corrosion, spalling, etc. Also, deep learning models can be implemented to analyze real-time data and to predict microscopic cracks, which is a next-to-impossible task for any human being. In this study, we explore the utilization of AI in various fields of civil engineering with a focus on the field of structural health monitoring. In this article, care has been taken to thoroughly investigate all the research done in the structural health monitoring (SHM) sector with the application of AI and its implications. Main emphasis has been given to the detection of different types of damage in a structural body using AI. Further, the research investigation has been narrowed down to the identification of cracks using this latest technology. Concrete conclusions have been drawn in the last segment, which highlights today's challenges and their limitations.

Keywords: Algorithm, artificial intelligence, crack detection, deep learning, machine learning, structural health monitoring

INTRODUCTION

The term artificial intelligence (AI) was first used by John McCarthy in a workshop held at Dartmouth, and it has since become popular [1]. AI is broadly a branch of computer science [2] that can provide solutions to complex real-life problems.

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The use of AI has spread rapidly throughout sectors of society in a short span of time. Its prediction and solution-providing capabilities ensure its use in finance, stock markets, company growth predictions, healthcare, remedy provisions, and drug testing [3–6]. Its ability to analyze and derive insights and patterns makes it an indispensable tool in social media data processing, record, and data maintenance, military strategies, and even judicial systems [7–10]. With the introduction of chatbots and the availability of AI tools, base algorithms have spread to the general public and are applied to schoolwork, assignment preparation, project research, data collection, creative work, and inspiration, and as an overall tool to navigate problems and find solutions (Figure 1) [11, 12].

Extensive research is also being conducted in various fields of engineering, aviation, and space industries [13, 14]. In this study, we explore and elaborate on the uses of AI in civil engineering. Civil engineering specializes in the creation, design, and maintenance of structures such as buildings, roads, bridges, transportation systems, and water supply facilities' infrastructure [15, 16]. Being a very large economic platform, the construction sector, which is a part of the Civil Engineering field, can shape national growth and long-term growth. So, it is a field that greatly impacts our everyday lives and determines the durability of man-made structures. It also considers the impact of the environment on these structures and their reverse effect.

As understood from these applications of civil engineering, particularly structural health monitoring (SHM), we can see that this field has large amounts of data regarding concrete specifications and stability, conditions, weather, and various values for the pressure and environment endured by the structure in question [17]. All these factors show that this is a data- and calculation-intensive field with great stakes, as the health of a building decides how safe it is for continued public use and when it should undergo maintenance or demolition.

Here, AI can record and compute data and conditions in real-time and perform calculations to predict future structural stability and implement preventive safety measures. These applications are further explored in detail in the present study.

RESEARCH METHODS

An extensive review of all previous research papers from the time of 2005 to date (2025) has been done here. For the source of these papers, academic portals like ASCE Library, Web of Science, Science Direct, Sage, Taylor and Francis, and Wiley Online Library have been used. Keywords like AI, artificial intelligence, use of AI in civil engineering, and application of AI in SHM were used to search for previous research works. To finalize or pick a particular article, a two-round article selection process was followed. Firstly, it was checked for matching keywords that appropriate keywords have been used or not. Secondly, the article was explored after thorough reading to lock the picked article in case it exactly matches the objective of the present work.

AI APPLICATION IN STRUCTURAL HEALTH MONITORING

SHM is a wider field that encompasses various practical and scientific concepts along with several varied engineering practices. The main objective of SHM is to correctly depict the up-to-date performance and condition of the structure.

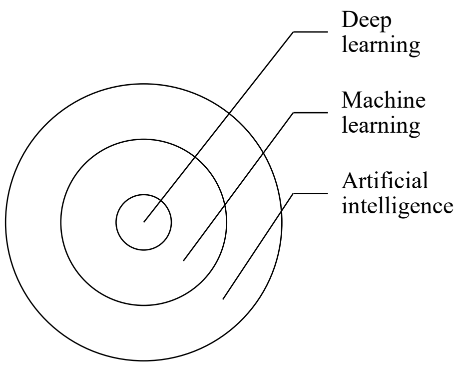

Figure 1. Artificial intelligence.
Source: Adopted from Stryker C, Kavlakoglu E. (2024). Artificial Intelligence. [online] IBM. Available from: https://www.ibm.com/think/topics/artificial-intelligence.

AI can successfully monitor real-time data of structures and thereby provide a variety of solutions to actual existing problems, which would be otherwise difficult to handle merely with conventional computational problems.

Smarsly et al. [18, 19] have demonstrated that the application of AI in monitoring the health of structures saves time and money. They discussed Conventional AI and Computational intelligence in their work.

In some recent reviews on the application of AI in civil engineering, the focus has been on structural engineering [20, 21]. These research works comprise the use of other sectors of civil engineering, the latest techniques and advancements of AI use for dealing with SHM by detecting damages prior to real-time failure [22]. worked especially on SHM with a key focus on design optimization. The authors have also discussed various algorithm techniques; for example, the application of a genetic algorithm for damage detection on the Tamar Bridge in the United Kingdom. In a similar research work [23], the authors explored the use of a genetic algorithm (GA) in the health monitoring of structures, particularly under harsh environmental conditions. They concluded that the GA technique applied in the researched work is quite capable of optimizing the positioning of multiple sensors, which is a must requirement for the prediction of structural real-time behavior under critical exposure conditions. In a few other research works, scientists and researchers have used another technology, which is a swarm intelligence-based algorithm [24, 25]. A hybrid algorithm used [26], that is, the integration of particle swarm optimization and the butterfly optimization algorithm along with the artificial neural network (ANN) technique, was successfully able to detect the depth of a single crack and a double crack in beams. The ANN technique was also used in a study [27] for damage detection in bridges.

Other than the above algorithms, nowadays the concept of Big Data and Deep Learning is also continuously gaining popularity due to its ability to handle any real and complex problems. The term big data is explained [28] as a combination of three Vs (volume, variety, and velocity) and two Vs (variability and veracity). Even in research work like [29], big data has been discussed with respect to structural health investigation.

Damage in structures can occur in various forms, such as cracks (dead or live), delamination or detachment, disintegration of structural materials, and spalling. It has been referred to as “damage is defined as changes to the material and/or geometric properties of these systems, including changes to the boundary conditions and system connectivity, which adversely affect the system’s performance.” [30]. It is evident from this definition that even a small change in the geometry of a structure can have a significant impact on its performance. It has been seen that the development of cracks is most likely to happen as a post-effect of corrosion, chemical attack, or weathering. Hence, in this study, more attention has been focused on crack detection and the corresponding methods.

The presence of cracks can be detected using two different approaches. The first approach is model-driven SHM. In previous studies [31–33], a crack was identified in a beam by updating the model. However, this approach has a disadvantage because of the lack of information regarding the joints and bonds in large and complex structures. Hence, the efficiency of the results may be compromised.

In the second approach, known as data-driven SHM, sensing devices help collect data from undamaged structures and, in a few cases, from damaged structures. In this case, the model is constructed using statistical pattern recognition, which uses machine learning algorithms [34, 35]. Usually, this approach has shown better results than the first approach.

RESEARCH GAPS

Many research papers have been reviewed for the completion of this work. However, only a limited number of research works have been highlighted here because of time and space constraints. Several techniques have been discussed and explored in previous research works; however, mostly these works were investigated under a controlled environment with a small-scale dataset. Hence, under actual exposure conditions, the results of the damage identification process may vary at different levels or may lead to inefficient results. In addition, difficulties related to data acquisition and preprocessing may arise in practice. Hence, it can be further investigated to better integrate SHM with large-scale datasets and real-exposure conditions.

It has been further observed that many previous works revolve around damage identification, mainly crack identification, rather than predicting crack growth or failure chances. Also, crack identification research works are siloed from other SHM techniques like non-destructive testing (NDT) tests. Hence, in addition to improving the efficiency of the results, the prediction of cracks is also essential. Furthermore, supplementing AI-based visual inspection with conventional NDT methods is important for crack characterization.

CONCLUSIONS

From the above literature review work, the following conclusions can be drawn:

1. The integration of SHM with AI has indeed revolutionized the field of civil engineering structures. Now, damage can be detected with less effort and less time; hence, its rectification has also become more cost-effective and beneficial for humankind.
2. Models based on deep learning have shown better performance in identifying and classifying cracks from image data. Hence, helping in reducing the risk of structural failures and enabling proactive maintenance. However, despite these advancements, several challenges persist that limit the widespread adoption and practical deployment of AI-based SHM systems.
3. Lack of large datasets and standardization are the main problems of AI-based solutions. In addition, issues such as the generalization of AI models to real environmental conditions, multimodal integration, and the prediction of crack propagation remain challenging for this field.
4. The application of AI to SHM is still growing, and many aspects remain unexplored. For the safety and serviceability of structures, decisions regarding repair and maintenance must be made at an appropriate time. For this, the outcomes of AI–SHM results must be provided to a 3D model through the use of light detection and ranging (LiDAR), photogrammetry, and vision-based measurements.

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