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Review article

Emerging artificial intelligence methods in structural engineering

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ABSTRACT

Artificial intelligence (AI) is proving to be an efficient alternative approach to classical modeling techniques. AI refers to the branch of computer science that develops machines and software with human-like intelligence. Compared to traditional methods, AI offers advantages to deal with problems associated with uncertainties and is an effective aid to solve such complex problems. In addition, AI-based solutions are good alternatives to determine engineering design parameters when testing is not possible, thus resulting in significant savings in terms of human time and effort spent in experiments. AI is also able to make the process of decision making faster, decrease error rates, and increase computational efficiency. Among the different AI techniques, machine learning (ML), pattern recognition (PR), and deep learning (DL) have recently acquired considerable attention and are establishing themselves as a new class of intelligent methods for use in structural engineering. The objective of this review paper is to summarize techniques concerning applications of the noted AI methods in structural engineering developed over the last decade. First, a general introduction to AI is presented and the importance of AI in structural engineering is described. Thereafter, a review of recent applications of ML, PR, and DL in the field is provided, and the capability of such methods to address the restrictions of conventional models are discussed. Further, the advantages of employing such algorithmic methods are discussed in detail. Finally, potential research avenues and emerging trends for employing ML, PR, and DL are presented, and their limitations are discussed.

1. Introduction

Civil engineering is fraught with problems that defy solution via traditional computational techniques. However, they can often be solved by an expert with proper training. Classical artificial intelligence (AI) has targeted this class of problems by capturing the essence of human cognition at the highest level. The term “AI” was introduced at a workshop held in Dartmouth college in 1956 [1]. AI is a computational method attempting to simulate human cognition capability through symbol manipulation and symbolically structured knowledge bases to solve engineering problems that defy solution using conventional methods. AI has been developed based on the interaction of various disciplines; namely, computer science, information theory, cybernetics, linguistic, and neurophysiology.

Several terms referring to artificial intelligence can be found in the literature, and they need to be identified to further elaborate on the state of the art. One of those terms is machine intelligence (MI). AI and MI are almost identical terms [2,3] and are often used interchangeably. MI is often considered a synonym of AI; yet it deals with different types of intelligent problems, e.g., clustering, classifications, computer vision, etc. In general, MI refers to machines with human-like intelligent behavior and reasoning, while AI refers to a machine’s ability to mimic the cognitive functions of humans to perform tasks in a smart manner. Another important term is cognitive computing (CC), which is inspired by human mind’s capabilities [4]. Cognitive systems are able to solve problems in a form mimicking humans thinking and reasoning. Such systems are based on the ability of machines to measure, reason, and adapt using learned experience [4,5]. The main characteristics of CC systems are their ability to interpret big data, dynamic training and adaptive learning, probabilistic discovery of relevant patterns. Technically, AI refers to computers and machines that can behave intelligently, while CC concentrates on solving the problems using humanlike thinking. The most significant difference between AI and CC can be defined in terms of interacting normally with humans. For any AI system, there is an agent that decides what actions need to be taken. However, CC systems learn, reason, and interact like humans. Therefore, it can be concluded that CC is essentially an AI agent, and as such CC is considered a sub-set of AI. Expert systems, on the other hand, is a

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branch of AI. As noted, AI is defined as the ability of a machine to mimic intelligent human behavior, seeking to use human-inspired algorithms to solve problems. Similarly, an expert system is defined as a computer program attempting to mimic human experts to solve problems demanding human/expert knowledge. It follows from the noted definitions that AI includes different branches such as expert systems, machine learning, pattern recognition, and fuzzy logic.

In recent years, there has been a growing interest in the use of AI in all engineering domains, and it has fueled many visions and hopes. While the civil engineering community has witnessed an extensive growth in the use of different AI branches/methods in its diverse areas, the present study concentrates on the AI methods that have gained significant attention over the last decade, namely machine learning (ML), pattern recognition (PR), and deep learning (DL) with a focus on their application to the structural engineering discipline. The scope of the review is to summarize the theoretical background of the methods, provide a historical context on their use, summarize the latest research developments, and discuss promising paths for future research.

The use of AI in civil engineering has been the topic of previous review articles. Adeli et al. [6] presented a multiparadigm learning technique, where the authors demonstrated that the performance can be notably enhanced by skillful integration of different AI branches, including neural networks, genetic algorithms, fuzzy sets, and parallel processing. An extensive study of evolutionary computation, a branch of AI, in the context of structural design was conducted by Kicinger et al. [7]. Lio et al. [8] carried out a review of studies concerning the application of metaheuristics as optimization techniques to address issues faced in the lifetime of a construction or engineering project. A survey on different AI methods (e.g., fuzzy logic, evolutionary computation, neural networks, swarm intelligence, expert systems, etc.) for civil engineering was conducted by Lu et al. [9]. Shahin et al. [10] studied applications of AI in geotechnical engineering; and Saka et al. [11] conducted a survey on mathematical and metaheuristic algorithms in design optimization of steel frame structures. Adeli et al. [12] carried out a review on progress in the optimization of high-rise buildings; and a survey on the applications and methodologies of the fuzzy multiple criteria decision-making techniques was conducted by Mardani et al. [13].

Recently, a survey on the application of multi-criteria decision making methods for the analysis of suspension bridges was conducted by Garcia-Segura et al. [14]; Sanchez et al. [15] presented a review on the applications of artificial neural networks, a branch of AI, for civil infrastructure that includes structural health monitoring, structural system identification, structural design and optimization, etc.; and a comprehensive state-of-the-art overview of sustainable structural design in green buildings rating systems and building codes was conducted by Pongiglione et al. [16]. Further, a survey on different AI methods (e.g., artificial neural networks, Bayesian, genetic algorithms, case-based reasoning, and fuzzy logic) for the field of fracture mechanics was performed by Khosravani et al. [17], while a literature review of application of multi-criteria decision analysis for aging-dam management was carried out by Mieza et al. [18]. Additionally, Sierra et al. [19] conducted a review on multi-criteria assessment of the social sustainability of infrastructures and Zavadskas et al. [20] surveyed the state-of-the-art methods applied to sustainable decision-making in civil engineering, construction, and building technology.

Although the noted review articles highlighted applications of AI in civil engineering structures/infrastructure, they mainly focused on traditional techniques and do not cover recent methods, such as PR, ML, and DL. Yet, these intelligent methods have experienced notable developments and increased use in structural engineering during the last few years. Therefore, this review paper presents a broad perspective of research efforts on the use of such emerging AI methods (i.e., PR, ML, and DL) in structural engineering during the last decade. Due to space limitations, the review emphasis for each paper was on the problem/issue being addressed, the domain and case structure being considered, and the AI method being used. The contributions of this review paper are: (1) study and summarize techniques concerning the applications of PR, ML, and DL in structural engineering over the last decade, (2) identify future directions and emerging trends for employing PR, ML, and DL in structural engineering applications, and (3) highlight current limitations of the reviewed AI methods in structural engineering.

The review paper is structured as follows. Section 2 presents the approach followed for selecting the reviewed literature and conducting the content analysis. A general introduction to AI is presented in Section 3, and the significance of AI in structural engineering is also described. New AI techniques (namely ML, PR, and DL) are introduced and highlighted in Section 4, where the differences of these techniques are elaborated. Section 5 reviews the application of such techniques in structural engineering. Further, Section 6 identifies potential research avenues and emerging trends for using the noted AI methods in future innovations, while highlighting the current limitations of such methods. Finally, conclusions are provided in Section 7.

2. Research method

The present study used content analysis [21] to select the reviewed literature. Content analysis is commonly used to objectively make valid inferences according to collected data with the aim of disclosing central aspects of previous studies. It further allows for qualitative and quantitative operations. As a result, content analysis is able to provide an inclusive disclosure of AI applications in structural engineering, leading to reliable results from the study.

Sample collection was performed in this study through the search and selection of peer-reviewed articles. Articles were collected from prominent and well-accepted academic databases. The procedure of literature search and selection for this study can be summarized as follows:

- The academic databases Web of Science, Scopus, Science Direct, ASCE Library, Engineering Village, Wiley Online Library, Sage, and Emerald were used for article search and selection.
- Keywords such as “artificial intelligence”, “artificial intelligence in civil and structural engineering”, “pattern recognition structural engineering”, “machine learning structural engineering”, “deep learning structural engineering”, “convolutional neural networks structural engineering”, and “computational intelligence” were used to search the databases. This resulted in the identification of academic articles concerning the application of AI methods in structural engineering. The time period under review was from 2009 to 2017, which led to the identification of approximately 430 candidate articles.
- The criteria for selecting the identified articles was the application of pattern recognition, machine learning, and deep learning in structural engineering. In accordance with such criteria, a two-round article selection technique was employed. That is, titles, abstract, and keywords of the noted articles were checked in the first round to ascertain if they meet the criteria. The second round consisted of reading and analyzing the entire article, thus ensuring that all of the selected papers were closely related to the review objective. Finally, 282 articles were selected and used for the present review.

For the review, qualitative and quantitative analyses were performed to identify the applications of emerging AI methods in structural engineering, the AI algorithms used for such applications, and analyze the applicability of these algorithms for the noted applications. This approach led to the identification of the most promising applications of emerging AI techniques and future research directions.