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MACHINE LEARNING METHODS IN CIVIL ENGINEERING: A SYSTEMATIC REVIEW

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Abstract. Machine learning has found applications across a range of commercial enterprises. One of the exciting industries impacted by AI has been civil engineering. The aim of this paper is to review recent developments in AI as they relate to civil engineering. We highlight potential applications as well as the risks.

1. Introduction

The recent advances in AI has catalyzed its adoption in many industries. In particular, the potential of AI in civil engineering can not be underestimated. Despite the vast potential benefits, there exist risks and challenges in implementing AI in civil engineering. The goal of this paper is to review recent trends in advances in applying AI and machine learning in civil engineering. We discusses opportunities for success and highlight potential pitfalls.

AI and machine learning have various applications in civil engineering, including structural engineering, transportation engineering, geotechnical engineering, and more [1]. These technologies can improve the efficiency of civil engineering projects by providing solutions to challenges such as damage inspection, safety risk management, and information modeling [1]. However, there are also challenges in applying AI and machine learning to civil engineering, such as the need to define the interface between humans and AI, collect detailed behavioral data, and address ethical considerations [39, 19, 34].

To address these challenges, researchers are exploring the integration of intelligent technologies like neural networks, big data, and deep learning throughout the full life cycle of civil engineering projects [39]. This cross-integration can promote the synergistic development of AI research in civil engineering .

In terms of future prospects, AI and machine learning have the potential to profoundly transform the development of civil engineering in areas such as urban planning, architectural design, structural design, engineering construction, service operation and maintenance, and disaster prevention and mitigation [**?**]. The use of AI techniques, such as deep learning, computer vision, UAV, 3D printing, BIM, virtual reality, and augmented reality, can lead to unmanned, fully

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automatic, intelligent urban and regional planning, as well as new technologies for civil engineering design, construction, maintenance, and disaster management [6].

Overall, the integration of AI and machine learning in civil engineering offers many possibilities for improving efficiency and addressing challenges. However, it is important to consider ethical considerations and continue research and development to fully realize the potential of these technologies in the field [19, 34].

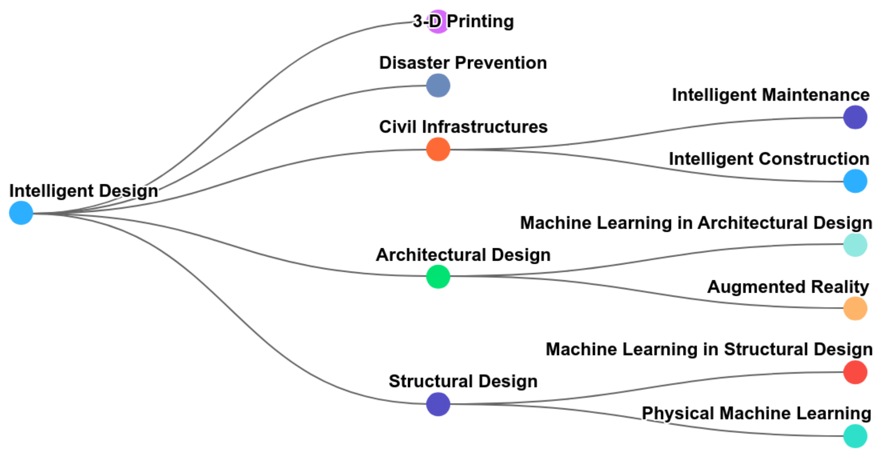

FIGURE 1. Applications of AI and machine learning in civil engineering.

2. Design and construction of civil engineering structures

AI and machine learning have various applications in optimizing the design and construction of civil engineering structures. We discuss the key points in the following passages:

2.1. **Civil engineering for structural design optimization.** The current applications of AI in civil engineering for structural design optimization include:

- AI and machine learning techniques are being used in structural engineering, transportation engineering, and geotechnical engineering to address challenges such as damage inspection, safety risk management, and information modeling [1].
- AI algorithms assist engineers in creating optimal structural designs by considering factors like cost limits, environmental circumstances, and material qualities [41].
- AI-based computational tools and information technology have become widely utilized for sustainable and effective design in civil engineering, particularly in seismic impact optimization and environmental sustainability [41].

One of the key challenges in many scenarios in civil engineering and beyond is the optimal feature set. Since, in the age of big data, not all the collected data is useful, it has become paramount to identify the optimal features in a subset [?].

2.2. **Challenges.** The challenges and limitations of using AI and machine learning in civil engineering for optimizing the design and construction of structures include:

- Challenges include data availability and effectiveness, defining AI models, ethical considerations, and the need for collaborative partnerships [16].
- The integration of AI in civil engineering poses questions about the future role of human engineers and the importance of engineering intuition and creativity [17].

2.3. **Efficiency and sustainability.** Contribution of AI and machine learning algorithms to the efficiency and sustainability of civil engineering structures include:

- AI technology, such as deep learning, machine learning, and reinforcement learning algorithms, is applied to civil engineering for urban intelligent planning, structural design, construction, maintenance, and disaster prevention [6].
- AI-driven robotics and autonomous machines contribute to enhanced efficiency and safety during construction by automating tedious jobs and continuously monitoring site conditions (Singh et al., 2023).
- AI-based methods in structural design optimization can decrease negative environmental impacts, improve resource allocation, and create a more time- and cost-effective design process [18].

Machine learning is bound to play an important role in sustainable development in many areas including civil engineering [**?**]. By utilizing the data-driven approach AI algorithms have the potential to uncover sustainable solutions that have hitherto escaped human detection.

2.4. **Future prospects.** The future prospects of AI and machine learning in revolutionizing the design and construction of civil engineering structures include:

- The use of AI in civil engineering has the potential to improve the efficiency, safety, and sustainability of infrastructure systems [16].
- AI can bring digitalization in the construction industry to a new level and create new services and business models [19].
- The ongoing research and development of AI-based methods in civil engineering indicate a growing interest in leveraging AI for contemporary, intelligent, safe, and resilient infrastructure [19].

AI and machine learning have diverse applications in civil engineering for optimizing structural design and construction. These technologies contribute to efficiency, sustainability, and safety in the field. However, challenges such as data availability and ethical considerations need to be addressed. The future prospects of AI in civil engineering are promising, with the potential to revolutionize the industry and create innovative solutions for infrastructure development.

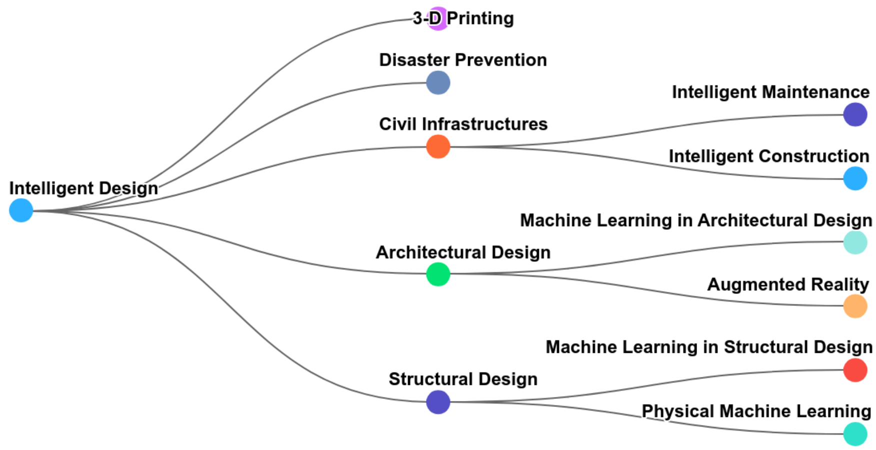

FIGURE 2. Applications Intelligent Design in civil engineering.

3. Prediction and mitigation of natural disasters

AI and machine learning have the potential to greatly impact the prediction and mitigation of natural disasters on civil engineering infrastructure. We discuss some of the key research uncovered in the literature:

3.1. **Disaster management.** There are several applications of AI in disaster management. AI is being utilized in various fields and industries, including disaster management. It is used in geospatial analysis, robotics, machine learning, and remote sensing, among others [20]. AI can provide quick and efficient responses characterized by increased speed, precision, and readiness in disaster management (Abid et al., 2023). It can also improve planning and analysis capabilities, facilitate situational awareness, and accelerate recovery efforts [20].

3.2. **Challenges.** There exist several challenges in using AI for predicting natural disasters. The use of AI for disaster risk analysis presents potential pitfalls that society must be cautious of [26]. Challenges that need to be overcome include the need for high-quality and diverse data, compatibility with existing systems and technologies, ethical and social implications, and ongoing research and development [27].

3.3. **Accuracy.** One of the key facets is improving accuracy of predicting natural disasters. AI models have shown remarkable success in handling huge and nonlinear data, making them perfect tools for disaster monitoring and management [28]. By leveraging AI techniques such as big data, machine learning, and deep learning, tasks in visualizing, analyzing, and predicting natural disasters can be facilitated [29].

3.4. **Ethical considerations.** Ethical considerations and risks of AI must be take into serious consideration. The use of AI in disaster management raises ethical considerations and potential risks. Data privacy and security are critical issues, as the use of AI often involves the collection and analysis of sensitive information . Additionally, there is a need to ensure that AI is developed and used in ways that are fair, equitable, and effective in reducing the impact of disasters [27].

3.5. **Key technologies.** The progress in AI applications is driven by the key technologies and methodologies. AI techniques such as machine learning and deep learning are commonly used in disaster management for tasks such as disaster and hazard prediction, risk assessment, early warning systems, and damage assessment [30, 62] . These technologies have the potential to enhance accuracy, decrease calculation time, and reduce model creation costs [38].

There exists a significant capacity for AI to improve the accuracy of predicting natural disasters and their impact on civil engineering infrastructure. However, there are challenges to overcome, including the need for high-quality data and addressing ethical considerations. Key technologies such as machine learning and deep learning are commonly used in disaster management for various tasks. It is important to ensure that AI is developed and used responsibly to mitigate the risks associated with natural disasters [27].

4. Maintenance and monitoring

The use of AI and machine learning algorithms in civil engineering systems and infrastructure maintenance and monitoring has the potential to bring numerous benefits, but also poses certain challenges and limitations. We summarize below the key issues:

(1) Current challenges in maintenance and monitoring of civil engineering systems and infrastructure:
   - Traditional methods fall short in adequately accounting for the complexity of infrastructure systems [16].
   - Limited visibility into how AI technology works and performs [33].
   - Barriers to collecting detailed behavioral data from humans and contextual environments [34].
   - Issues with data availability and effectiveness, defining AI models, and ethical considerations [16].

(2) Key applications of AI and machine learning in civil engineering systems and infrastructure maintenance:
   - Structural health monitoring, damage inspection, and safety risk management [**?**].
   - Optimization of construction processes, project scheduling, resource allocation, and risk assessment [16].
   - Accurate estimation of soil properties, foundation construction, and transportation planning [16].
   - Infrastructure monitoring, including bridge inspection, pipeline integrity assessment, and defect detection [16, 35].
   - Condition assessment, health state prediction, and maintenance optimization (Cline et al., 2017).

(3) Potential benefits of using AI and machine learning for monitoring civil engineering systems and infrastructure:

- Improved efficiency, safety, and sustainability of infrastructure systems ([16].
- Enhanced decision-making based on meaningful insights from data (Shandilya et al., 2022).
- Reduction of errors and quick results through quick decision-making [38].
- Automation of structural inspection and assessment tasks [35].

(4) Limitations and risks associated with the use of AI and machine learning in civil engineering systems and infrastructure maintenance:

- Uneven development of intelligence at various stages and limitations in practical applications (Liu et al., 2024).
- Challenges with data availability, AI model definition, and ethical considerations [16].
- Need for collaborative partnerships and overcoming knowledge gaps [34].
- Potential impacts on job site injuries and industry business models [40].

AI has the potential to significantly improve the maintenance and monitoring of civil engineering systems and infrastructure. However, challenges such as data availability, model definition, and ethical considerations need to be addressed. Collaborative efforts and further research are necessary to fully harness the benefits of AI in civil engineering.

5. Structural design optimization

Using AI algorithms to optimize the structural design of civil engineering projects has the potential to improve efficiency and sustainability. Several types of AI algorithms can be applied in this context, including natural language processing, machine learning, neural networks, and deep learning [41, 18, 42, 43]. However, there are key challenges and ethical considerations to consider when using AI algorithms in this field.

Key challenges in using AI algorithms to optimize the structural design of civil engineering projects include the need for improvement in requirement documents and information management [44]. Additionally, there is a need for method development and knowledge gap identification in this field [44]. Ethical considerations and potential risks associated with using AI algorithms include the need for data privacy and security, potential bias in algorithmic decision-making, and the impact on employment in the construction industry [45, 16].

In terms of comparing AI algorithms to traditional methods in optimizing the structural design of civil engineering projects, AI algorithms offer advantages such as enhanced decision-making, automation of tedious tasks, and the ability to consider multiple aspects such as cost limits, environmental circumstances, and material qualities (Singh et al., 2023). Traditional methods may fall short in adequately accounting for the complexity of civil engineering projects [19]. However, it is important to note that AI algorithms should not replace human engineers, but rather serve as tools to assist and enhance their work [17].

There is an enormous potential to optimize the structural design of civil engineering projects by improving efficiency, sustainability, and decision-making using modern AI technology. However, there are challenges and ethical considerations that need to be addressed. AI algorithms offer advantages over traditional methods, but should be seen as tools to assist human engineers rather than replace them.

6. Forecasting the likelihood and severity of natural disasters

Forecasting has become one of the key applications of machine learning in many areas of scientific endeavour [**?**]. Using AI and machine learning algorithms to analyze historical data can help predict the likelihood and severity of future natural disasters on civil engineering infrastructure. However, there are several key challenges and ethical considerations associated with this approach as summarized below.

Data quality and diversity plays a crucial role. High-quality and diverse data are crucial for accurate predictions. However, obtaining such data can be challenging, as it may be limited or incomplete [46]. Additionally, integrating different types of data, such as geospatial data, social media data, and wireless network sensor data, can be complex [46].

Another key issues is compatibility with existing systems. Integrating AI and machine learning algorithms with existing civil engineering infrastructure can be challenging. It requires ensuring compatibility and interoperability between different systems and technologies (Adams et al., 2022).

Ethical considerations and biases must be taken into account. The use of AI and machine learning algorithms for predicting natural disasters raises ethical considerations and potential biases. There is a need to ensure fairness, transparency, and accountability in the algorithms and models used [60]. Biases can arise from biased training data or algorithmic biases.

Different types of AI and machine learning algorithms that can be used to predict the likelihood and severity of natural disasters on civil engineering infrastructure include:

(1) Machine learning algorithms, such as supervised, unsupervised, and reinforcement learning, can be used for disaster prediction, risk assessment, and early warning systems [38, 62].
(2) Deep learning algorithms, a subset of machine learning, can be used for tasks such as hazard prediction, risk assessment, disaster detection, and damage assessment [62].
(3) Artificial neural networks, including recurrent neural networks and convolutional neural networks, are effective in processing spatial information and can be used for weather forecasting, healthcare, and flood detection [61].

There exist several ethical considerations and potential biases associated with using AI and machine learning for predicting natural disasters on civil engineering infrastructure. Ensuring fairness and transparency in the algorithms and models used is crucial to avoid biases and discrimination [60]. Biases can arise from biased training data, which can lead to inaccurate predictions and unfair outcomes [60]. There is a need for accountability in the development and use of AI and machine learning algorithms to ensure responsible and ethical practices [60].

Integrating AI and machine learning algorithms with existing civil engineering infrastructure can improve disaster preparedness. There exist multiple approaches in this field. AI algorithms can provide quick and efficient responses characterized by increased speed, precision, and readiness, improving decision-making in disaster management [20]. Utilizing remote sensing, geographic information systems, and AI analyses can improve planning and analysis capabilities, facilitate situational awareness, and accelerate recovery efforts [20]. AI can help address challenges in disaster management by integrating with climate modeling and traffic management systems, leading to more efficient systems for emergency management operators and improved resilience [59].

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