Journal of World Architecture, 2024, Volume 8, Issue 2
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Research and Application of Deep Learning Technology in Prefabricated Buildings

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Abstract: Prefabricated buildings have become an important development trend in the field of modern architecture because of their high efficiency and environmental friendliness. Artificial intelligence and deep learning technology have been increasingly applied in prefabricated buildings. Deep learning technology provides comprehensive optimization of building design, construction, quality control, and cost and schedule management through the learning and analysis of large amounts of data. This paper aims to explore the application of deep learning technology in prefabricated buildings, analyze the revolutionary changes it brings in different stages, and discuss the problems faced when implementing this technology.

Keywords: Deep learning; Prefabricated building; Application

Online publication: May 20, 2024

1. Introduction

The rise of prefabricated buildings stems from the urgent need to improve efficiency, cost control, and environmental protection of construction projects. With the growth of the global population and the acceleration of urbanization, the problems faced by traditional construction methods such as large resource consumption, long construction periods, high labor intensity, and severe environmental pollution have become increasingly prominent. Prefabricated buildings achieve industrialization and standardization of construction production by prefabricating components in factories and then transporting them to the construction site for assembly, thereby overcoming the bottleneck of traditional construction methods. The introduction of deep learning technology is an important driving force for the innovation of prefabricated buildings, providing efficient design optimization and decision support for prefabricated buildings, improving building performance and resource utilization, ensuring construction quality and safety, and further promoting the development of prefabricated buildings in the direction of intelligence, efficiency, and sustainability.

2. The principle and main application scope of deep learning technology

Deep learning technology is a subfield of machine learning based on the complex structure and algorithm of artificial neural networks, especially the deep neural network structure, namely deep neural networks [1]. By imitating the mechanism of the human brain in processing and interpreting complex data, the deep learning model learns representations and features from a large number of data and carries out high-level abstractions. This learning ability is realized by building a multi-layer network structure, and each layer transforms the input data and extracts higher-level features. The layers are connected by weights and trained by the backpropagation algorithm. The weights are automatically adjusted to minimize discrepancies between forecast and actual results. Deep learning has a wide range of applications, with significant performance in image recognition, object detection, image segmentation, face recognition, video analysis, and other fields. Convolutional neural networks (CNNs) are the core technology in this field. It is widely used in language models, machine translation, sentiment analysis, and text generation [2]. Recurrent neural networks (RNNs) and transformer networks (such as BERT, and GPT series) signify significant breakthroughs in this field. Speech recognition and deep learning technology accurately recognize human speech in noisy environments with the help of long short-term memory networks (LSTMs) and CNNs. In addition, deep learning technology has been showing great potential in disease diagnosis, drug discovery, medical image analysis, and other fields.

3. Classification of deep learning techniques

3.1. Supervised learning

Supervised learning is the core paradigm of deep learning technology, which relies on labeled training data to learn the mapping relationship between input and output. The model is trained by analyzing the data set with correct answers, so that the model can identify the relationship and pattern between the data, and that it can be applied to new and unseen data for prediction or classification after the training is completed. In supervised learning, commonly used algorithms include support vector machines (SVM), decision trees, random forests, gradient lift trees, and deep neural networks [3]. In particular, deep neural networks such as CNNs are used in image recognition and video processing, while RNNs and transformer networks (BERT and GPT) are used in natural language processing. The main challenge in supervised learning is the large amount of labeled data needed to train the model. The labeling process is usually time-consuming and laborious, and the performance of the model highly depends on the quality and diversity of the data. Insufficient or biased data will lead to the poor generalization ability of the model and the risk of overfitting.

3.2. Unsupervised learning

Unsupervised learning aims to explore the internal structure and distribution characteristics of unlabeled data. Unlike supervised learning, unsupervised learning does not rely on externally provided label information but finds the regularity and structure of data by analyzing the characteristics of the data itself. It performs data clustering, distribution estimation, reduction, and feature learning. The key algorithms of unsupervised learning include K-means clustering, hierarchical clustering, Gaussian mixture models, principal component analysis (PCA), autoencoders, and generative adversarial networks (GANs) [4]. The autoencoder learns the effective representation of the data by compressing the data and then reconstructing it. Generative adversarial networks can generate high-quality data by pitting generators and discriminators against each other. The challenge of unsupervised learning lies in extracting useful information from unlabeled data and evaluating the results of model learning. Due to the lack of clear guidance signals, model training and result interpretation are more complex than supervised learning. This makes determining the most appropriate data representation, dealing with high-dimensional data, and addressing the problem of data noise and outliers the key obstacles in unsupervised learning [5].

3.3. Semi-supervised learning

Semi-supervised learning, located between supervised learning and unsupervised learning, is an effective strategy for dealing with limited annotated data in deep learning [6]. Semi-supervised learning uses a large amount of unlabeled data and a small amount of labeled data to improve the model's learning efficiency and generalization ability by integrating the distribution information of the unlabeled data and the guidance information of the labeled data. It is suitable for situations where the acquisition cost of labeled data is high and the labeling process is time-consuming. The main techniques of semi-supervised learning include self-training, multi-view learning, the Tookey method, and generative adversarial networks. The self-training method involves training the model with labeled data, using the model to predict the unlabeled data, followed by selecting the data points with the most reliable prediction results to be added to the training set [7]. Multi-view learning is based on the assumption that different views can provide complementary information and improve learning. By constructing a representative graph of the data points, the unlabeled data can be labeled through the correlations established between the nodes in the graph. The generative adversarial network generates simulation data by training the generative network, and the discriminant network improves the model's ability to distinguish between real data and simulation data. The main challenges of semi-supervised learning include designing effective algorithms to utilize the information of unlabeled data, ensuring the stability and generalization ability of the model, and evaluating the contribution of unlabeled data to the model performance. It also faces the risk of inconsistent data distribution, insufficiently labeled data, and excessive dependence of the model on a small amount of labeled data [8].

3.4. Reinforcement learning

Reinforcement learning focuses on how to guide the agent to make decisions based on environmental feedback. The core of reinforcement learning is that the agent learns the optimal strategy, that is, a series of decisions, to maximize the cumulative reward obtained by interacting with the environment, performing actions, and receiving feedback (reward or punishment). In reinforcement learning, agents need to find a balance between exploring unknown environments and using known information. The key algorithms include Q learning, time-difference learning, Monte Carlo method, deep Q network, trust domain strategy optimization (TRPO), and soft actor-critic algorithm (SAC). Reinforcement learning has a wide range of applications, ranging from games, autonomous driving, and robot control, to financial strategy optimization and natural language processing. However, the environment may be extremely complex and dynamic, and the reward signal may be sparse and delayed [9]. In addition, designing effective reward functions, dealing with high-dimensional state space and action space, and ensuring the stability and efficiency of the learning process are all key issues faced in the field. In recent years, deep reinforcement learning has shown much potential in solving high-dimensional perception and decision problems. Nevertheless, it also brings new challenges such as low sample efficiency, hyperparameter adjustment difficulties, and limited algorithm generalization ability. Therefore, integrating model-driven and data-driven methods, improving the sample efficiency of algorithms, and enhancing the interpretability and stability of models are key areas of the development of reinforcement learning.

4. Advantages and disadvantages of prefabricated buildings

4.1. Advantages of prefabricated buildings

Prefabricated construction is a modern construction technology in which building components are pre-produced in a factory and transported to the construction site for assembly. This technology is favored in the construction industry for its high efficiency, environmental friendliness, and quality control. Since most of the components are prefabricated in the factory and only need to be assembled on site, the construction period is shortened, and the construction can be carried out in a controlled environment, ensuring construction quality and accuracy and reducing the uncertainty and risk of on-site construction [10]. In addition, prefabricated buildings have less impact on the environment, and factory production can effectively reduce noise, dust, and waste during on-site construction, contributing to the realization of green buildings and sustainable development. Prefabricated buildings also have high flexibility and reusability. Building components can be designed and adjusted easily, and they can be disassembled and reassembled in future renovation and upgrading, thereby improving resource utilization [11]. At the same time, the standardized production and modular design of prefabricated components contribute to cost control and budget management and improve the economic efficiency of the entire project.

4.2. Problems in the construction of prefabricated buildings

Prefabricated components are usually large and heavy, requiring special transportation, and the transportation distance and path have a significant impact on the cost and timeliness. On-site assembly requires high precision, and the accumulation of errors may lead to difficulties in assembly. High-precision manufacturing and positioning technology is required to ensure the accurate docking between components. Compared with traditional buildings, prefabricated buildings require most of the detailed design and decision-making to be completed in the design stage, requiring a high level of skill and teamwork of the design team. Besides, they also require a high degree of standardization and modularity during the construction process and effective communication and coordination with multiple suppliers. Market acceptance and regulatory restrictions may also present obstacles to prefabricated buildings. Due to the inertia of traditional construction methods and unfamiliarity with new technologies in the market, owners, designers, contractors, and users may be skeptical of prefabricated buildings. Besides, existing building regulations and standards may not be fully applicable to prefabricated buildings, so it is necessary to update and improve regulations to support the application of new technologies [12]. Although prefabricated buildings may have cost advantages in the long run, the initial investment in mold making, special equipment, and research and development is relatively high, so the size and complexity of the project and the long-term return are key factors determining its economic benefits.

5. Application of deep learning technology in prefabricated buildings

5.1. Design optimization

Deep learning technology can carry out parametric design in the initial stage of building design. By training neural network models, the impact of different design parameters on building performance such as energy efficiency, structural stability, and material cost can be predicted. Deep learning models such as CNNs and RNNs are used to deal with complex geometric shapes and patterns. They assist designers in creative design while ensuring the manufacturability and assembly of components. Besides, they classify and label building components automatically and accelerate the collation and exchange of design information. Based on image recognition and object detection technologies, different components and materials can be automatically identified from the design drawings, achieving rapid information extraction and compilation [13]. In addition, generative models using deep learning, such as GANs, can generate a variety of design schemes, providing designers with rich reference and inspiration. However, in the optimization of prefabricated building design, factors like technical and functional issues, as well as aesthetics, cultural and social factors, and the integration and evaluation of soft factors need to be considered, making them important aspects in the future development of deep learning technology [14].

5.2. Automation of construction processes

Deep learning technology revolutionizes the automation of prefabricated building construction, optimizing processes, enhancing safety, and boosting efficiency through intelligent algorithms. Integrated into visual monitoring systems on construction sites, it ensures real-time safety monitoring, identifies risks like unauthorized entry, and analyzes worker behavior to prevent accidents. Furthermore, by analyzing video data, deep learning tracks progress, automatically categorizes construction phases, and offers valuable data for project management [15]. Deep learning optimizes construction resource allocation and scheduling, analyzing historical data and site conditions to enhance material supply chain management with predictive models. It predicts resource demand, automates mechanical equipment and human resource scheduling, and supports robot and automation equipment deployment. For instance, neural networks train drones and robots for autonomous navigation on construction sites, enabling tasks like material transportation, monitoring, and quality inspection [16].

5.3. Quality control and monitoring

In terms of quality monitoring, deep learning can be used to analyze images and videos to achieve real-time monitoring of the quality of the construction process and finished products. This approach allows the accurate identification of defects like cracks and deformations or non-compliant installation so that appropriate measures can be taken promptly. Furthermore, in material and component quality control, deep learning analyzes material composition, structure, and performance data to predict material performance and lifespan. It optimizes material selection and production stages and monitors the production process to ensure component size and structure meet design requirements [17].

5.4. Cost and schedule management

For cost management, deep learning predicts project costs, analyzes influencing factors, and optimizes budget allocation. It identifies key cost factors like material prices and labor costs, offering forecasting and optimization suggestions. Real-time cost data monitoring detects budget deviations promptly, enabling preventive measures to prevent overspending [18]. Besides, deep learning technology enhances project schedule planning and monitoring accuracy and efficiency. It analyzes historical schedule data, current construction status, and external factors like weather and supply chain conditions to identify delay risks and propose mitigation strategies. Applied dynamically, it adjusts project plans, optimizes resource allocation, and ensures progress as planned.

6. Conclusion

In summary, deep learning technology in prefabricated construction holds considerable promise for enhancing project efficiency and quality. It optimizes design, automates construction, ensures quality control, and manages costs and schedules effectively. However, further integration of deep learning requires overcoming challenges in data processing, model training, and interpretability. As technology advances and industry practices evolve, deep learning is poised to play a pivotal role in prefabricated buildings, driving the industry toward intelligence, efficiency, and sustainability.

Funding

School-level scientific research project of Guangdong Baiyun University in 2023: Research and Application of Deep Learning-Driven Prefabricated Building Assembly Scheme Design System, (Project number: 2023BYKY09).

Disclosure statement

The author declares no conflict of interest.

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