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Application of Intelligent Construction in Underground Space: Technical Integration and Field Overview

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Abstract. With the acceleration of urbanization, the development of underground space is evolving towards clustering. The high missed inspection rate and high operation and maintenance costs of traditional manual inspection highlight the urgency of intelligent transformation. This paper systematically organizes the existing technologies in the field of intelligent construction of underground space through literature analysis and case combing, covering technology chains and application scenarios, aiming to overview the development status of this field. The research finds that multi-modal perception networks can achieve multi-dimensional and accurate perception of the underground environment, and dynamic digital twin technology and AI modeling methods can break through the difficulties of modeling geological uncertainties. Intelligent control equipment can significantly improve construction efficiency. However, problems such as the lack of standardization of multi-source data, insufficient cross-scale modeling efficiency, and high costs of intelligent equipment restrict the large-scale application of technology. In the future, it is necessary to promote the transformation of underground engineering from experience-driven to data-intelligent-driven through paths such as interdisciplinary collaborative modeling, standard system construction, and data security guarantee. This research provides a reference for the current status of technologies for the intelligence of underground engineering, and has practical significance for optimizing the allocation of urban space resources and supporting the construction of new urbanization.

Keywords: Intelligent Construction, Underground Space, Digital Twin, Intelligent Perception, Intelligent Decision-making

1. Introduction

With the in-depth advancement of the urbanization process, underground space, as the "second space" for urban development, has seen an explosive growth in its development and utilization demands. The annual development volume of underground space in China has exceeded 840 million square meters. Landmark projects such as the Shanghai North-South Passage have achieved the construction of multi-dimensional structures with a depth of 48 meters, highlighting the remarkable trend of underground space development evolving towards "deep, large-scale, and clustered" [1]. However, the development of low-altitude space faces severe technical challenges. For example, the missed inspection rate of traditional manual inspection in the identification of concealed diseases is

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as high as 27%. In contrast, intelligent construction technology can reduce the missed inspection rate while cutting down the operation and maintenance costs by 30%, which also reveals the urgent demand of the industry for intelligent transformation [2-4]. The core methods to break through the current predicament mainly focus on three aspects, namely the improvement of the precision and robustness of intelligent perception in the underground unstructured environment, the support of multi-source heterogeneous data for the dynamic evolution of digital twins, and the guarantee of the generalization ability of intelligent decision-making under complex geological conditions [1,2,4,5]. Among them, the Spot robot of Boston Dynamics has achieved sub-millimeter-level monitoring of construction progress. The DigTwin project has established the digital twin standard for underground pipe networks. The accuracy of deep learning in the classification of tunnel surrounding rocks reaches 91.5%, and the intelligent control technology of shield machines improves the construction efficiency by 46% [2-4, 6]. However, existing research still has significant gaps in the collaborative modeling across scales (micro-geology-macro-structure) and the determination of the intelligent standard system, which seriously restricts the large-scale application of the technology [2,7,8].

Therefore, through literature and case analysis, this paper aims to construct a complete technical system of "perception-modeling-decision-execution" to reveal the application of intelligent construction in underground space. The research systematically sorts out the technology chains and application scenarios of intelligent construction in underground engineering. This research provides a systematic solution direction from the theoretical level to solve the problems of safety, economy, and sustainability in the development of urban underground space. According to the research, the strategies for the construction of the standard system and ethical safety guarantee are proposed, which have important strategic significance for supporting the construction of new-type urbanization and optimizing the allocation of urban space resources.

2. Research methods

To comprehensively sort out the application status of intelligent construction technologies in underground space, this research adopts a method that combines bibliometric analysis and qualitative analysis to systematically organize relevant literature. The literature retrieval covers core Chinese and English databases, including CNKI (China National Knowledge Infrastructure), Web of Science, and IEEE. Considering the extensiveness of the "intelligent construction" field and the diversity of its definitions, keywords are expanded to ensure the comprehensiveness of retrieval. The keywords mainly include "underground space", "intelligent construction", "digital twin", "smart sensing", "intelligent decision-making", etc. By randomly combining these keywords, the search scope and results are expanded. Moreover, using the criteria of topic (strongly related to "underground space" and "application of intelligent construction technologies"), publication type (journal), and publication time (2020-2025), the 626 retrieved documents are screened, and finally 57 valid documents are included. In addition, the documents are classified and divided according to technical links (perception, modeling, decision-making, execution) and application scenarios (construction, operation and maintenance), forming a two-level classification system, which provides a structured basis for subsequent technical sorting.

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3. Sorting out the core technologies of intelligent construction in underground space

3.1. Intelligent perception and data acquisition technology

The complexity of the underground space environment imposes stringent requirements on the perception accuracy and data reliability of intelligent construction. The multi-modal perception network has emerged as the core technological approach to overcome this predicament. Distributed optical fiber sensing (BOTDR), leveraging its advantages of distributed and long-distance monitoring, can collect and provide observation data over long periods and distances. In ultra-deep underground projects such as the Shanghai North-South Passage, BOTDR has achieved the high-precision capture of surrounding rock deformation at 0.01mm/m, providing data support for the structural safety early warning of the project [1]. In the micro-seismic monitoring system, BOTDR can identify the micro-fracture signals of rock masses and issue early warnings for disasters such as rock bursts 48 hours in advance, thereby significantly enhancing the ability to control construction risks [2]. However, the relatively high complexity of the underground environment also poses a threat to BOTDR. For example, water vapor erosion will increase the drift rate of optical fiber sensors, and the electromagnetic environment will greatly reduce the signal-to-noise ratio of micro-seismic sensors, making it difficult to maintain the stability and accuracy of data collection over the long term.

To overcome the limitations of a single sensing technology, representative solutions for multi-technology integration are constantly emerging. The collaborative application of three-dimensional laser scanning and ground-penetrating radar (GPR) demonstrates unique value in the reconstruction of urban underground pipe networks. Laser scanning reconstructs the geometric shape of pipelines through high-density point clouds, while GPR penetrates the underground medium to obtain information about the material and burial depth of pipelines. After the integration of the two, the point cloud matching error can be accurately controlled within 2mm, effectively solving the problems of low efficiency and poor accuracy of traditional manual surveying [4,7]. This “optical-electromagnetic” dual-mode perception technology enables the multi-dimensional analysis of the physical characteristics of underground space and enhances the perception robustness in complex environments through data complementarity, providing a fundamental support for the accurate decision-making of intelligent construction.

3.2. Digital modeling and intelligent analysis technology

The concealment of underground space and the complexity of geological conditions require modeling and analysis technologies to have the capabilities of dynamic evolution and precise prediction. The construction of dynamic digital twins and AI modeling methods have become the core breakthroughs for this problem. In long linear underground projects such as subway tunnels, the Physical Entity-Virtual Model-Connection-Data-Service (PE-VM-CN-DD-SS) achieves the prediction of rock stratum dip angles with an error of $< 3°$ by fusing the detailed structural model of BIM with the macroscopic geological information of GIS and dynamically updating it in combination with borehole data [4,8]. In addition, underground engineering has shifted from "static design" to "dynamic evolution" management, providing a digital foundation for the optimization of construction schemes and risk pre-control. AI modeling methods further deepen the analysis of the complex behaviors of underground engineering. CNN (U-Net), relying on its strong ability to extract image features, can accurately locate the range of defects in the identification of tunnel lining water leakage, with the intersection over union (IoU) of segmented regions reaching 0.87 [2]. The LSTM-

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GNN coupling model combines the time-series modeling advantages of long-short-term memory networks with the spatial correlation analysis capabilities of graph neural networks, breaking through the prediction difficulties of multi-parameter coupling during the tunneling process and reducing the root mean square error (RMSE) of shield machine torque prediction by 23% [1,2]. In addition, the Physics-Informed Neural Network (PINN) innovatively integrates geotechnical mechanics theories such as Terzaghi's formulas with real-time monitoring data, effectively improving the prediction accuracy of surface settlement and achieving the deep integration of "mechanism guidance-data correction" [2,6]. These AI models break through the hypothetical constraints of traditional numerical simulation and provide algorithm support that is more in line with actual conditions for the intelligent decision-making of underground engineering.

3.3. Intelligent decision-making and control execution technology

The autonomy and automated construction system of construction machinery are the key supports for the implementation of intelligent construction, ensuring the precision of construction decision-making and the efficiency of execution. In shield tunneling construction, the reinforcement learning algorithm breaks through the traditional experience-based control mode. By learning the correlation between real-time geological feedback and construction parameters, it dynamically optimizes the earth pressure control strategy, greatly enhancing the safety of ultra-deep and ultra-long tunnel construction. The standard deviation of surface settlement is reduced from 15mm to 8mm [2,4]. Relying on the GA-Bi-LSTM model, which integrates the global search advantage of the genetic algorithm and the time-series learning advantage of the bidirectional long-short-term memory network, it can assist cross-sea tunnel projects in accurately adapting to complex marine geological conditions and improving the tunneling speed. Meanwhile, by intelligently adjusting the cutting parameters of the tools, the intelligent algorithm drives the autonomy of construction machinery, which can be used to reduce the wear rate of machinery.

In addition, the automated construction system can reshape the construction mode of underground space. The 3D printing technology for tunnel linings abandons the traditional formwork erection and pouring processes. Relying on the intelligently controlled printing robotic arm, it demonstrates high-efficiency and flexible advantages in scenarios such as lining of irregular cross-sections and rapid construction of emergency channels [3]. With the help of visual recognition and precision control algorithms, the modular segment assembly robot replaces manual work to complete the entire process of segment grabbing, transportation, and assembly, and controls the positioning accuracy within ±3mm. While improving construction efficiency, it avoids the risks of working at heights and in narrow spaces [4].

4. Application scenario cases

4.1. Construction stage

In the tunneling scenario of tunnel engineering, the integration of the physical detection of geological radar and the AI advanced prediction model can reduce the risks and uncertainties in the construction stage of underground space by reshaping the construction mode. Through the intelligent interpretation of radar echo signals, the identification of unfavorable geology (faults, karst caves, etc.) can be effectively improved, with the recognition rate jumping from 65% to 89%, providing a basis for the dynamic adjustment of tunneling schemes and the precise control of support timing [2,6]. However, under complex geological conditions, such as in water-rich fault zones, the

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disturbance of groundwater will cause the distribution law of geological parameters to change abnormally, reducing the generalization ability of the AI model. This requires optimizing the model according to changes in the scenario during implementation, and enhancing the adaptability of the model to extreme working conditions through strategies such as incremental model training [2,9]. In addition, relying on the integration of multiple technologies to build a "perception-analysis-early warning" closed loop, the micro-seismic monitoring system captures the rock mass fracture signals, and through the processing of the CNN-LSTM model, it can accurately warn the construction team of rock bursts during the construction stage, with an accuracy rate of 85%, buying time for construction personnel and equipment to avoid risks [2]. The AI video monitoring based on deep learning algorithms can effectively identify behaviors such as not wearing safety helmets and illegally entering dangerous areas, achieving real-time interception of potential safety hazards [3,5]. However, the electromagnetic interference and uneven lighting in the underground environment still affect the data quality. In the future, it is necessary to optimize the sensor layout and algorithm robustness, promoting the upgrade of safety monitoring from "post-event tracing" to "pre-event prevention and control", and fortifying the intelligent safety defense line in the construction stage.

4.2. Innovation in intelligent management

During the Operation and Maintenance Stage During the operation and maintenance stage of underground space, it is necessary to ensure the long-term safety of the structure and the efficient operation of facilities. This includes structure detection and fault early warning. The management mode upgrade provided by intelligent technology can improve maintenance efficiency while keeping costs low, thus increasing the service life of the underground space. In the field of structural health monitoring, the tunnel lining crack detection system relies on the MobileNet-V3 lightweight network. Combined with the high-frame-rate images dynamically collected by the track inspection vehicle, it can accurately capture the subtle changes of cracks and achieve a recognition speed of 30fps [2,10]. The digital twin system built in the underground utility tunnel integrates the real-time data of sensors with the BIM model of facilities. It can predict equipment faults in advance, reducing the maintenance cost by 22% and promoting the transformation of operation and maintenance from "passive repair" to "active prediction"[4,7]. At the same time, digital twins and RFID tags can increase the efficiency of asset inventory to 70%, realizing the whole-life-cycle traceability of pipelines and equipment [4,7]. In the operation and maintenance of deep-sea tunnels, the ROV robot equipped with multi-beam sonar can complete structure detection at a water depth of 500 meters, solving the problems of high risk, low efficiency, and high cost of traditional diving operations [1,9].

5. Discussion

Intelligent perception and data acquisition have achieved multi-dimensional perception. However, the lack of multi-source data standardization leads to poor interoperability, including difficulties in aligning BIM component coding with GIS geographic coding, and obstacles to integration due to differences in sensor data formats and precisions [4,7-8]. In addition, the impact of extreme environments (such as high humidity, strong electromagnetic fields, etc.) on perception stability still needs to be overcome. In terms of digital modeling and intelligent analysis, dynamic digital twins and AI models have improved modeling precision, but the efficiency of cross-scale (from micro-geology to macro-structure) collaborative modeling is insufficient. For example, a single update of the finite element geological inversion model takes a long time, making it difficult to match the

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construction rhythm [2]. Moreover, the generalization ability of models is restricted by complex geological conditions, such as a decline in prediction precision in water-rich fault zones [2,9].

In addition, in terms of intelligent decision-making and control execution, although intelligent equipment has improved construction efficiency, the cost threshold of the equipment is relatively high. The initial investment in AI-driven shield machines and assembly robots is 2.5-3 times that of traditional equipment, which seriously restricts the application in small and medium-sized projects [3,4]. Additionally, there is a shortage of compound talents, that is, technical personnel who master both engineering and machine learning, which has led to obstacles in the practical application and implementation of technologies [5,6].

Currently, quantum computing has demonstrated application potential, compressing the multi-physical field simulation time for tunnel excavation from 48 hours to 6 hours, providing an efficient tool for the pre-simulation of complex geology [4,8]. Therefore, the future technical direction focuses on promoting its large-scale application in cross-scale modeling.

6. Conclusion

This paper sorts out the core technologies and application status of intelligent construction in underground space, covering aspects such as intelligent perception (multi-modal sensor fusion), digital modeling (dynamic digital twin and AI models), intelligent decision-making and execution (autonomous equipment), as well as the full-scenario practices in construction and operation and maintenance. The existing technologies have achieved remarkable results in improving perception precision, modeling capabilities, and construction efficiency, but still face bottlenecks such as multi-source data standardization, cross-scale modeling efficiency, and cost control.

Future development needs to focus on improving the data standardization system, enhancing cross-scale modeling efficiency, reducing the cost of intelligent equipment, and promoting the engineering application of new technologies such as quantum computing. This research provides an overall reference for the industry on the current status of technologies, helping the development of underground space to transform towards data-intelligent driving.

However, this paper also has some shortcomings. Firstly, it only analyzes and studies the application of intelligent construction in underground space based on literature, without involving the verification of relevant technologies and optimization schemes. In addition, the literature coverage of this paper is relatively small and mainly concentrated in the engineering-related direction. In the future, investigations and information accumulation in relevant fields will be increased, further research on the application of intelligent construction will be conducted, and by supplementing the breadth of literature, strengthening quantitative analysis, and extending the research boundaries, the systematic understanding of the application of intelligent construction in underground space will be further enhanced, providing more solid support for the technological iteration and standard construction of the industry.

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