A Review of Intelligent Robot Applications in Rail Transit

Short Communication

ABSTRACT

[Purpose] To address the escalating operational and maintenance pressures resulting from the expansion of urban rail transit systems, this study establishes three progressive research goals: (1) to construct a technical classification framework for intelligent inspection robots based on locomotion modes (rail-mounted, wheeled, tracked, and quadruped), clarifying the functional boundaries and applicable conditions of each category within typical operational scenarios; (2) to quantitatively evaluate the actual effectiveness of intelligent inspection robots in terms of inspection efficiency, data standardization levels, and operational safety, while systematically identifying critical bottlenecks including environmental adaptability, intelligent decision-making capabilities, collaborative operation mechanisms, and cost control; and (3) to propose a development pathway for an integrated intelligent system covering the complete "inspection-diagnosis-maintenance" workflow, thereby providing actionable decision-making foundations and technical roadmaps for the intelligent transformation of operational and maintenance paradigms. [Method] Based on the aforementioned classification framework, this study synthesizes representative case studies from recent years to systematically summarize the technical characteristics, applicable scenarios, and inherent limitations of each robot category. [Results] Empirical evidence demonstrates that various types of intelligent inspection robots can effectively improve inspection quality, enhance data acquisition standardization, and reduce safety risks in diverse operational environments such as subway tunnels, underground passages, and rail vehicle depots. However, several critical challenges persist in current applications, including limited environmental adaptability under complex terrain and extreme weather conditions, insufficient autonomous intelligence for complex decision-making, difficulties in achieving collaborative multi-robot operations, and relatively high costs associated with deployment and maintenance that hinder large-scale promotion.[Conclusion] Future research and development efforts should concentrate on breakthroughs in key enabling technologies, including multi-modal locomotion, intelligent perception and decision-making, and human-robot collaboration. The ultimate objective is to construct an integrated intelligent O&M ecosystem that encompasses the entire process chain of "intelligent inspection—fault diagnosis — predictive maintenance," thereby providing robust technological support for the safe, efficient, and sustainable development of modern urban rail transit systems.

Keywords: intelligent robot; urban rail transit; railway maintenance robotics; locomotion mode.

1. INTRODUCTION

As an efficient and environmentally friendly public transportation mode, urban rail transit undertakes increasingly heavy urban passenger transport tasks . Since the 1980s, the metro system in China has developed rapidly, with continuous growth in total mileage and the number of operational lines, evolving from a nascent stage to one of the most extensive metro networks in the world. The rapid expansion of urban metro networks has brought great convenience to public travel and significantly alleviated traffic congestion caused by China's large population and fast-paced urbanization process, thereby contributing substantially to sustainable urban development and improved quality of life for residents. With the continuous expansion of metro system scale and the increase of service years, inspection and maintenance work to ensure safe and reliable metro operation has become increasingly critical, demanding more sophisticated approaches to address the growing complexity of infrastructure management .The national Outline for Building a Strong Transportation Country and the China Association of Metros' Outline for the Development of Smart Urban Rail Transit in China have successively proposed that, with intelligent robots, big data, Internet of Things (IoT), and other technologies at the core, vehicle operation and maintenance should be driven toward "digitalization and intelligentization" transformation, marking a strategic shift toward modernizing traditional maintenance paradigms through advanced technological integration (Zhao, Z., Hu, F., & Wang, C. 2024).

During long-term operation, vibration, wear, acceleration, deceleration, and braking of metro trains can easily lead to bolt loosening of undercarriage structural components, pipeline detachment, equipment friction, or deformation, all of which pose potential safety risks if not detected and addressed promptly. Undercarriage inspection points are characterized by numerous occlusions, dim lighting, and narrow spaces, creating substantial difficulties for human inspectors to perform thorough and accurate examinations (Li, L. 2022). Moreover, manual inspection must be conducted late at night after operations cease, which imposes significant physical and mental burdens on inspection personnel and affects inspection efficiency, as workers must operate under fatigue-inducing conditions with limited time windows to complete comprehensive checks (Wang, Z. 2023).

Against the backdrop of smart urban rail construction, research on intelligent robotic systems holds important theoretical and practical significance for promoting the transformation of maintenance models and ensuring safe train operation. Most existing studies either focus on core technologies of intelligent robots or concentrate on their software-hardware system integration and specific morphological design, while systematic reviews of the overall development context, practical challenges, and future trends of intelligent robots remain insufficient. Therefore, this paper reviews various types of intelligent robots and conducts comprehensive analysis from the perspectives of current development status, problems, and challenges of intelligent robots, aiming to provide references for the application and development of intelligent robots in the rail transit field and to bridge the gap between technological innovation and practical implementation in metro maintenance operations. This study systematically searched CNKI and Web of Science to ensure comprehensive coverage of both Chinese and English literature.

2. Development Status of Intelligent Robots in Rail Transit

Based on locomotion modes, robots can be broadly categorized into four distinct types: rail-mounted, wheeled, tracked, and legged configurations. Each locomotion paradigm exhibits unique operational characteristics and is optimally suited for specific application domains within intelligent inspection systems.Rail-mounted robots are primarily employed for tunnel driving hole inspection, moving systematically along fixed tracks to ensure precise positioning and stable operation in linear infrastructure environments. These systems excel in scenarios requiring high-repeatability navigation and consistent spatial orientation, where predetermined trajectories eliminate the need for complex path planning algorithms.Wheeled robots are predominantly deployed for safety passage inspection or electromechanical equipment room patrol missions, capitalizing on their superior mobility characteristics and operational efficiency when traversing flat, structured surfaces. Their mechanical simplicity and energy efficiency make them ideal candidates for routine surveillance tasks in well-maintained indoor facilities and corridor networks. Tracked robots are principally utilized for penetrating confined spaces such as smoke exhaust channels and cable galleries to conduct thorough inspections, deriving significant advantages from their exceptional traction properties and robust obstacle-crossing capabilities when operating within narrow, debris-laden environments. The distributed ground contact pressure and continuous track mechanisms enable these platforms to negotiate challenging terrain that would incapacitate conventional wheeled configurations.Legged robots are chiefly applied to complex unstructured terrain exploration, emergency rescue operations, and specialized mission profiles requiring anthropomorphic mobility. Through their biologically-inspired adaptive gait patterns and dynamic balance control strategies, these sophisticated platforms can successfully traverse irregular surface topologies and negotiate dynamically evolving obstacles that defy traditional locomotion approaches.Robots embodying diverse locomotion morphologies each demonstrate distinctive competitive advantages when deployed across various rail transit inspection scenarios. Their operational applicability maintains intimate correlation with environmental complexity parameters, the degree of structural regularity present in the target workspace, and the specific technical requirements inherent to mission objectives. This multimodal landscape of robotic mobility solutions furnishes system designers with a comprehensive portfolio of technical implementation pathways, enabling the development of intelligent inspection architectures precisely calibrated to address the unique constraints and opportunities characteristic of heterogeneous operational contexts.

2.1 Rail-mounted Robots

Rail-mounted robots are automated execution units that operate along predetermined tracks, suitable for continuous inspection scenarios in structured environments. The robot body is equipped with a high-definition dual-camera module and a voice intercom system, integrating various functional sensors such as temperature, humidity, and gas detectors. Combined with dedicated hardware and intelligent software systems(Kim, H., & Choi, Y. 2025), it can achieve functions such as image and voice recognition, multi-source data remote transmission, remote control, and environmental state perception, effectively improving inspection safety and quality while reducing labor intensity and operational costs. However, rail-mounted robots are constrained by fixed paths, making it difficult to flexibly respond to track failures, adapt to layout changes, or cross-zone inspections, and the installation and maintenance costs of tracks are relatively high. Motion control focuses on smooth start-stop operations and operational safety, with accurate positioning required for both manual and automatic modes to ensure reliable data collection.In 2022, China Mobile Beijing Company developed the "AI Intelligent Inspection Robot", as shown in Figure 1(a). This robot's data collection is not affected by subjective factors, featuring high timeliness, consistency, and low error rates(de Andrade Lira, R. V., de Siqueira Campos, A. L. P., Gomes Neto, A., et al. 2022). In 2023, Wang Shuo researched a rail-mounted robot capable of alleviating the pressure of manual inspection tasks, as shown in Figure 1(b), achieving precise navigation and positioning as well as motion control stability for substation rail-mounted inspection robots under complex electromagnetic environments. In 2024, Li Lincang proposed a solution for fully automated inspection robots and conducted research on key technologies including mechanical structure, motion control, and infrared detection, ultimately achieving the detection and positioning of high-temperature electrodes in power equipment, as shown in Figure 1(c). In 2024, Zhang Guoming et al. developed a mining rail-mounted robot, as shown in Figure 1(d), implementing a power-source-free design for inspection robots through energy harvesting technology to improve the accuracy of abnormal fault detection in hazardous underground environments. The above review summarizes progress in rail-mounted robots regarding structure, control, and perception, demonstrating their effectiveness in inspection safety and efficiency. However, limitations remain: excessive focus on technology with insufficient cost assessment, underexplored strategies for path constraints, and immature multi-source perception integration. The literature scope is also narrow, lacking international cutting-edge research and cross-industry comparisons.

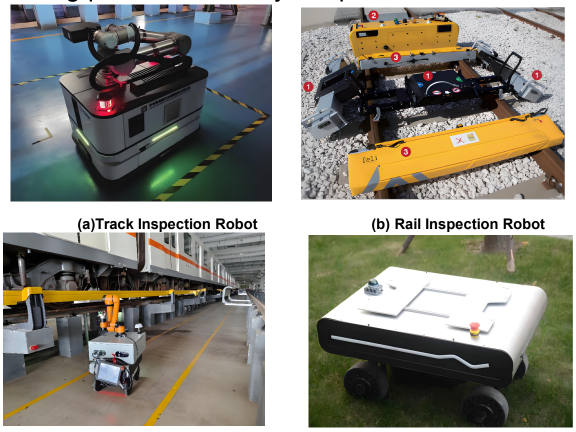
(a) Power Equipment Inspection Robot (b) Data Center Intelligent Inspection Robot

(c) High-Temperature Electrode Detection Robot (d) Mining Rail-Mounted Robot

Fig. 1. Rail-mounted robots

2.2 Wheeled Robots

Wheeled robots primarily rely on wheels for ground locomotion and are suitable for inspection tasks on flat surfaces and structured environments. They are typically equipped with high-precision sensors such as LiDAR, ultrasonic sensors, and inertial measurement units to achieve autonomous navigation, precise localization, and comprehensive environmental perception. These robots are fitted with elevating camera systems, including optical imaging cameras and infrared thermal cameras, which respectively perform high-definition video image acquisition, equipment status monitoring, and fire alarm detection during the inspection process(Sun, C., Wu, H., Yang, Z., et al. 2025). Wheeled locomotion represents one of the most widely adopted approaches in mobile robotics due to its flexible mobility, simple mechanical structure, low manufacturing cost, and high mechanical efficiency. On flat ground, wheeled robots can move rapidly with minimal energy consumption; however, they are prone to sinking or slipping on soft, uneven, or smooth surfaces, limiting their applicability in challenging terrains. In 2023, Zhu Jiangyong et al. (Zhu, J., Li, P., Li, X., et al. 2023) conducted research on the positioning system of intelligent inspection robots for urban rail transit vehicles, as shown in Figure 2(a), addressing robot positioning error issues in track trench environments through multi-sensor fusion algorithms. In 2023, Loccioni developed a wheeled mobile robot named Felix, as shown in Figure 2(b), for automatic inspection of railway switches and crossings, capable of generating real-time assessment reports and predictive analyses based on machine learning algorithms . In 2024, Yu Die investigated a global path planning algorithm based on search step optimization and verified the robot's positioning accuracy as well as its excellent autonomous navigation and obstacle avoidance capabilities through physical experiments in simulated rail transit scenarios, as shown in Figure 2(c). In 2025, Chen Shushuai designed and analyzed a four-wheel eight-drive mobile chassis robot system for train inspection, as shown in Figure 2(d), validating the feasibility of both static and dynamic obstacle avoidance through comprehensive field tests. However, existing literature still shows notable limitations: most studies remain confined to single technical modules such as localization or path planning, lacking exploration of system integration in full-scale operations; standardized evaluation metrics are absent, making cross-study comparisons difficult; experiments rely heavily on idealized environments rather than real-world dynamic scenarios, raising reliability concerns; and cost-benefit analyses together with long-term maintenance strategies are insufficient, limiting practical industry adoption.



(a)Track Inspection Robot (b) Rail Inspection Robot

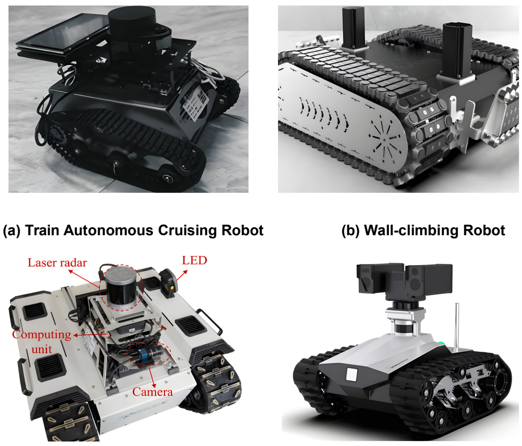
(c) Autonomous Navigation Inspection Robot (d) Inspection Mobile Obstacle Avoidance Robot

Fig. 2. Wheeled Robots

2.3 Tracked Robots

Tracked robots are mobile robots that utilize a track system for locomotion, possessing exceptional terrain adaptability to perform tasks in rugged, unstructured environments. The tracked walking mode provides relatively low ground contact pressure and distributed weight distribution, making it suitable for soft, muddy, or uneven terrain where wheeled robots would struggle. However, the track structure also results in inferior flexibility and maneuverability of tracked robots, particularly in terms of turning radius and energy efficiency on hard surfaces. Additionally, their performance is constrained in extreme or dynamically changing environments such as high-temperature, severe cold, or highly corrosive conditions due to material limitations and mechanical wear.

In 2024, Wei Qiong et al.(Wei, Q., Guo, C., Zhang, D., et al. 2024) conducted research through simulation and real-vehicle experiments on path planning optimization for tracked robots. Their improved algorithm can effectively enhance the quality of planned paths, reduce navigation deviations, and elevate the autonomous cruising capability and intelligent level of tracked robots in complex environments, as shown in Figure 3(a). In 2024, Shenzhen Jichuang Robot Technology Co., Ltd.(Zhu, J., Zhu, Y., & Zhang, P. 2024) developed a general-purpose wall-climbing robot model GECKO-MA600, as shown in Figure 3(b), which utilizes magnetic adhesion and tracked locomotion to operate on vertical metallic surfaces and can carry specific functional modules such as cameras or sensors according to different operational requirements, avoiding direct friction with walls and reducing surface damage. In 2024, Wei Guo adopted the Bunker tracked mobile robot as the carrying platform for crack detection in infrastructure maintenance, completing image capture and inspection tasks through automated traversal to achieve high-precision, automated crack detection in complex enclosed environments (Guo, W., Liang, G., Ren, S., et al. 2024), as shown in Figure 3(c). In 2025, Jing Zongqiang et al. (Jing, Z., Liu, Y., Cao, M., et al. 2025) explored a tracked robot integrating multi-sensor information including visual, inertial, and ranging sensors, as shown in Figure 3(d), whose coordinated optimization of path planning and real-time motion control strategies effectively improved its autonomous locomotion capability, stability, and obstacle negotiation performance in complex terrain. The above literature shows progress in tracked robots for path planning, modular design, and multi-sensor fusion. However, existing research has notable limitations: insufficient assessment of system-level reliability and engineering validation; inadequate strategies for addressing inherent limitations; and limited exploration of heterogeneous information coordination and adaptive decision-making.



(a) Train Autonomous Cruising Robot (b) Wall-climbing Robot

(c) Crack Detection Robot (d) Multi-sensor Inspection Robot

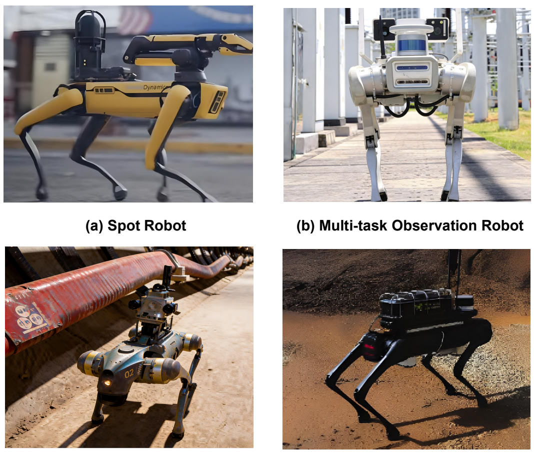
Fig. 3. Tracked Robots

2.4 Quadruped Robots

Quadruped robots represent a sophisticated class of biomimetic robotic systems meticulously engineered to approximate biological appearance and behavior through the emulation of fine anatomical structures, locomotion principles, and behavioral characteristics inherent in natural organisms. These advanced robotic platforms demonstrate remarkable capabilities in executing complex missions within dynamic and unstructured environments. By integrating diverse sensor payloads, they facilitate the acquisition of high-resolution environmental data while exhibiting exceptional mobility characteristics and superior terrain adaptability when operating under challenging conditions (Fuławka, K. M., Koval, A., Nikolakopoulos, G., et al. 2025). Nevertheless, several inherent limitations constrain their practical deployment in demanding applications. Specifically, their relatively modest load-bearing capacity, constrained operational endurance due to battery limitations, and elevated maintenance requirements render them suboptimal for sustained, high-intensity inspection operations within subway infrastructure environments. Furthermore, the mechanical complexity introduced by multiple degrees of freedom, intricate structural configurations, and numerous articulation points substantially elevates the difficulty coefficient associated with motion control, thereby necessitating sophisticated precision control methodologies and advanced control algorithms.

Boston Dynamics, a pioneering entity in legged robotics, introduced Spot Mini, a compact quadruped robot actuated by brushless electric motors, as illustrated in Figure 4(a). This highly agile platform incorporates an externally mounted robotic manipulator that significantly enhances its functional versatility by assisting in object manipulation and task execution, thereby demonstrating exceptional intelligence and collaborative operational capabilities . In 2025, Liu Xiaoluo and colleagues (Liu, X., Chen, Y., Liu, J., et al. 2025) implemented digital twin technology to establish comprehensive real-time monitoring of quadruped robot operational status and mission execution parameters. Their innovative system architecture incorporates a remote task distribution mechanism that enables unified coordination and intelligent scheduling of multiple robotic assets, as depicted in Figure 4(b). Concurrently in 2025, Wang Shuhan et al. (Wang, S., Zhang, Y., & Song, Z. 2025) conducted systematic investigations into motion control strategies, real-time data transmission protocols, and three-dimensional information visualization techniques specifically tailored for quadruped robotic systems deployed in underground cable tunnel environments. The resulting robotic platform exhibits highly efficient data acquisition and processing capabilities, thereby furnishing reliable technical support for intelligent management of tunnel infrastructure engineering projects, as shown in Figure 4(c). Additionally in 2025, Liu Xinwei and collaborators (Liu, X., Wu, P., Zhang, B., et al. 2025) developed a specialized quadruped robot radiation monitoring system designed to fulfill routine environmental nuclear radiation dose rate surveillance requirements. This system additionally demonstrates operational efficacy in critical applications including nuclear emergency response operations, remote radiation monitoring missions, and large-area contamination assessment surveys, as illustrated in Figure 4(d).

The above literature systematically reviews the technological progress of quadruped robots, fully demonstrating their significant advantages in complex terrain adaptability and mission flexibility. However, existing research still has several limitations worth reflecting on: studies mostly focus on functional validation and scenario exploration, lacking attention to system reliability; insufficient research on strategies to address the inherent limitations of quadruped robots; and research on multi-robot coordination and intelligent scheduling remains at a preliminary stage.



(a) Spot Robot (b) Multi-task Observation Robot (c) Cable Data Acquisition Robot (d) Radiation Monitoring Robot

Fig. 4. Quadruped Robots

3. CONCLUSION

Intelligent inspection robots are gradually becoming a key technical enabler for the digital and intelligent transformation of urban rail transit operation and maintenance modes. Through a systematic review of rail-mounted, wheeled, tracked, and quadruped robot systems, this study finds that these robots have demonstrated significant technical advantages in scenarios such as tunnel inspection, depot detection, and equipment condition monitoring. Their deployment has effectively improved inspection efficiency, enhanced operational safety, and promoted data standardization, providing strong support for the intelligent upgrading of rail transit maintenance systems. However, (1) research on the continuous multi-interface operation capability of multimodal locomotion mechanisms across rails, ground, walls, and other surfaces remains blank; (2) existing robot systems generally lack deep integration with existing rail transit operation and maintenance information systems; (3) insufficient research has been conducted on human factors engineering and safety mechanisms under human-robot collaborative operation; (4) there is a lack of empirical research on life-cycle cost-benefit analysis of robot deployment. On this basis, corresponding future research directions are proposed respectively, which are consistent with the critical analysis presented earlier. Prospective research and development initiatives should strategically concentrate on achieving critical technological breakthroughs in several domains: innovative multi-modal locomotion mechanisms capable of traversing heterogeneous terrain conditions, advanced intelligent perception systems integrated with sophisticated decision-making fusion algorithms, seamless human-robot collaboration frameworks, and comprehensive standardized integration protocols. These concerted efforts will facilitate the emergence of a fully integrated intelligent ecosystem encompassing the complete operational workflow of "inspection-diagnosis-maintenance," thereby furnishing robust technical support for the construction of safe, highly efficient, and environmentally sustainable urban rail transit O&M infrastructures.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Author has declared that no competing interests exist.

REFERENCES

Zhao, Z., Hu, F., & Wang, C. (2024). Research and application of "digital intelligence + natural person" collaborative inspection mode for Nanjing Metro electric multiple units. Modern Urban Transit, (12), 29-35.DOI:10.20151/ j.cnki.1672-7533.2024.12.005. (in Chinese)

Li, L. (2022). Function and application analysis of subway vehicle underbody inspection robot. Urban Mass Transit, (S1), 82-85+89.DOI:10.16037/j.1007-869x.2022.S1.019. (in Chinese)

Wang, Z. (2023). Key technologies and application schemes of intelligent inspection robots. Urban Mass Transit, (S1), 102-105.DOI:10.16037/ j.1007-869x.2023.S1.021. (in Chinese)

Kim, H., & Choi, Y. (2025). 3D location estimation and tunnel mapping of autonomous driving robots through 3D point cloud registration on underground mine rampways. Underground Space, 22, 1-20. DOI:10.1016/j.undsp.2024.10.003.

de Andrade Lira, R. V., de Siqueira Campos, A. L. P., Gomes Neto, A., et al. (2022). Elliptical UHF sensor for partial discharge detection. Sensors and Actuators A: Physical, 348, 113981. DOI:10.1016/j.sna.2022.113981

Sun, C., Wu, H., Yang, Z., et al. (2025). Robotic s imulation systems and intelligent offline tea ching for urban rail transit maintenance. El ectronics, 14(12), 2431-2431.DOI:10.3390/ electronics14122431.

Zhu, J., Li, P., Li, X., et al. (2023). Positioning system of urban rail transit vehicle intelligent inspection robot. Railway Transport and Economy, 45(01), 130-136. DOI:10.16668/ j.cnki.issn.1003-1421.2023.01.19(in Chinese)

Wei, Q., Guo, C., Zhang, D., et al. (2024). Global path planning considering tracked robot steering characteristics. Journal of Hubei University of Technology, 39(02), 57-62. DOI:10.3969/j.issn.2095-7386.2024.02.012. (in Chinese)

Zhu, J., Zhu, Y., & Zhang, P. (2024). Review of advancements in wall climbing robot techniques. Franklin Open, 100148. DOI:10.1016/j.fraope.2024.100148

Guo, W., Liang, G., Ren, S., et al. (2024). Automatic crack detection method for high-speed railway box girder based on deep learning techniques and inspection robot. Structures, 68, 107116. DOI:10.1016/j.istruc.2024.107116

Jing, Z., Liu, Y., Cao, M., et al. (2025). Design of automated control system for tracked robot based on multi-sensor fusion. Electronic Components and Information Technology, 9(03), 44-47. DOI:10.19772/j.cnki.2096-4455.2025.03.014. (in Chinese)

Fuławka, K. M., Koval, A., Nikolakopoulos, G., et al. (2025). Autonomous mobile inspection robots in deep underground mining—The current state of the art and future perspectives. Sensors, 25(12), 3598. DOI:10.3390/s25123598

Liu, X., Chen, Y., Liu, J., et al. (2025). Application research of quadruped robots in intelligent manufacturing systems. Space Electronic Technology, 22(05), 10-16.DOI: 10.3969/j.issn.1674-7135.2025.05.002

Wang, S., Zhang, Y., & Song, Z. (2025). Application research of quadruped bionic robots in tunnel surveying and monitoring. Intelligent City, 11(06), 6-8. DOI: org/10.19301/j.cnki.zncs.2025.06.002.(in Chinese)

Liu, X., Wu, P., Zhang, B., et al. (2025). Design and application of quadruped robot radiation monitoring system. Chinese Journal of Frontier Health and Quarantine, 48(03), 328-331.https://doi.org/10.16408/j.1004-9770.2025.03.025.(in Chinese)