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A Review and Prospect of Excavator Intelligence

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ABSTRACT

Excavators are important equipment in many construction projects. In the process of intelligentisation, the technological advancements they have undergone are no longer covered solely by hydraulic technology, but are being explored from multiple perspectives towards the integration of mechanical, electrical, and hydraulic systems. In recent years, the industry has made certain progress in three-dimensional environmental perception and remote operation, and some key technologies have initially established a foundation for engineering applications. However, due to the poor robustness of perception systems and the difficulty of establishing accurate models under complex working conditions, a high level of autonomous operation capability cannot yet be achieved. These issues need to be addressed in the future for excavators to enter the era of intelligentisation.

KEYWORDS

Excavator; Intelligent; Environmental Perception; Trajectory Planning; Remote Control; Digital Twin; Autonomous Operation.

1. INTRODUCTION

Excavators are widely used and operate under harsh conditions among construction machinery. In fields such as mining, construction, and emergency rescue, excavators frequently undertake tasks in environments with high dust levels, significant vibrations, heavy loads, and dramatically changing terrains, which demands high skill from operators, involves heavy work, and carries certain risks. Although traditional manual operation has been extensively developed and is now highly refined, issues with precision control, continuous work, and coordination in complex environments are becoming increasingly prominent. Therefore, excavators are also an ideal subject for research into the intelligentisation of construction machinery.

Recent research and applications have shown that intelligent excavators have achieved commercialisation. Related solutions have been tested and put into use in various enclosed or hazardous environments such as mines, ports, smelting plants, and rescue sites, including 5G remote-controlled hydraulic excavators, 3D navigation autonomous driving excavators, and unmanned excavators [1][2], marking the transition of this field from theoretical research to practical application.

From a technical composition perspective, the intelligence of excavators does not simply involve replacing a certain control software or adding some sensors and displays, but rather encompasses an overall integration of the hydraulic system, electronic control system, perception network, communication links, task management, and maintenance support. According to Cao Youke's research on the intelligence of hydraulic excavators, even when the basic mechanical structure and hydraulic system of excavators are relatively mature, there is still considerable room for progress in intelligence and automation [1]. This design scheme integrates functions such as intelligent controllers, three-dimensional intelligent vision systems, intelligent digging, intelligent loading, and intelligent anti-tipover measures, reflecting the contemporary understanding of "system-level intelligence".

In recent years, work has mainly focused on the closed-loop of autonomous operations. Based on the entire autonomous operation process of excavators, Ding Pan and others have decomposed the task into three parts: visual target detection, autonomous navigation, and trajectory tracking. On this basis, they use a method combining LSTM and DDPG [3], indicating that current research focuses are no longer simply on improving a specific action or local control loop, but rather on emphasising the connections and interactions between perception, decision-making, and execution.

2. THE DEVELOPMENT TRAJECTORY OF INTELLIGENT EXCAVATORS

The intelligent development of excavators follows a certain progressive process. In the initial research phase, the focus was mainly on aspects such as working device trajectory tracking, electro-hydraulic servo systems, and control methods, aiming to enable the working device to move stably along a given trajectory. Yu Huiting and others applied fuzzy algorithms and genetic algorithms combined with adaptive control for automatic excavation trajectory control and proposed a trajectory control system framework consisting of an electro-hydraulic servo system, controller, pressure sensor, angle sensor, joystick, and human-machine interface [4]. This also provides technical support for the transition of excavators from "experience-driven" to "compute-feedback-optimise".

On this basis, the focus of research has shifted from single trajectory tracking to comprehensive control of the entire robot. Tan Chen and others have studied that an intelligent hydraulic excavator is an integrated piece of equipment consisting of the working device, hydraulic system, travelling device, control system, rotation device, power device, and electrical system, and it operates in three states: normal mode, remote control mode, and intelligent control mode [5]. In the intelligent control state, the operator sets a work task in advance, and the computer automatically generates an optimal path, continually comparing it with the actual current path and making corresponding adjustments during execution. The remote control mode uses cameras, remote monitors, and PLCs to achieve long-distance manipulation. This indicates that excavator intelligence is evolving from 'action automation' to 'mode intelligence'.

With continued attention and research from the industry and academia, the intelligent technology system for excavators is gradually taking shape. Lu Liang and others have summarised that excavator intelligence primarily includes aspects such as perception, planning, control, monitoring, and fault diagnosis, encompassing technologies like pose perception, environmental perception, task planning, behavioural decision planning, motion trajectory planning, safety protection, real-time monitoring, and fault diagnosis [6]. In recent years, both domestic and international companies have increased their efforts in developing intelligent products, resulting in a continuous rise in relevant patent applications and a shift in market competition from individual functional competition to the overall system competition.

The development direction of accelerating the intelligence of large equipment in mining scenes, such as those involving Chunping Lian and others, is towards platformisation. In terms of the development of intelligent functions for large domestic mining excavators, the focus is currently on safety protection, condition monitoring, health management, and remote control. In the future, the trend will shift from the intelligence of individual equipment to collaborative intelligence among multiple pieces of equipment [7]. In other words, performing high-level intelligence on excavators in enclosed and high-risk working conditions serves as an excellent testing ground.

3. KEY TECHNOLOGIES FOR THE INTELLIGENTISATION OF EXCAVATORS

(1) Environmental perception and pose perception

Environmental perception is a prerequisite for the intelligence of excavators and a condition that all subsequent operations must meet. Perception is mainly divided into three categories: pose perception, environmental perception, and other auxiliary perceptions [6]. Pose perception refers to the measurement of the posture of the machine body and the working device, usually using methods such as photoelectric, electromagnetic, potentiometer, and inclinometer. Environmental perception involves constructing a model of the construction site using cameras, LiDAR, millimetre-wave radar, or a combination of these devices. Auxiliary perception includes material recognition and automatic weighing. Therefore, an intelligent excavator must not only be able to "know how it moves" but also "know the environment it is in."

Li Guihai and others, from the perspective of environmental perception, proposed a method for generating dense maps that removes the influence of dynamic objects, which can effectively improve the demand for good environmental maps during autonomous driving of excavators. By using camera poses and field of view overlap to select key frames for point cloud stitching, navigable environmental maps can be obtained [8]; simultaneously, Liu Wusong and others designed a data acquisition platform incorporating various environmental perception devices and developed related software, enabling the automatic identification of excavation targets through methods based on multi-layer ground extraction and feature extraction [9]

In terms of visual perception, monocular and binocular vision were compared. Binocular vision can accomplish tasks such as three-dimensional reconstruction and localisation through spatial triangulation, offering better recognition capabilities, but it requires higher specifications and more complex equipment. Monocular vision can be used in combination with LSTM methods for object detection and input. Earlier binocular recognition work by Xiao Ting and others was primarily aimed at unmanned excavation control. The system structure consists of three parts: visual recognition, actuator drive, and motion detection. After obtaining the target volume and its relative position to the excavator through binocular vision, the microcontroller controls the tracks and actuators to move the excavator towards the target for excavation [10], which also indicates that the concept of "recognise the target—estimate the position—take action" was considered at an early stage

(2)Trajectory Planning and Motion Control

Trajectory planning and motion control are important components of excavator intelligence. The trajectory control system of a hydraulic excavator's working device mainly consists of the boom, stick, bucket, and the hydraulic cylinders connecting them. By continuously receiving feedback from angle sensors and comparing it with the previously established target trajectory, the corresponding errors are obtained, allowing the working device to move along the predetermined trajectory. However, due to the complexity of construction sites, the variability of external conditions, high-order nonlinearities, and significant external disturbances, conventional PID control cannot achieve the desired results, thus more robust methods are required to address this issue.

Regarding this issue, the technical route for intelligent trajectory control is gradually becoming clear. Liu Jian and others proposed that the foundation of intelligent trajectory control for excavators is the electrification of traditional hydraulic systems. By then selecting suitable sensors, establishing a mathematical model of the working device, and solving for the trajectory, programmed mechanical movements can be achieved. The object of trajectory control is mainly the tip of the bucket tooth, and the system needs to respond according to the difference between the current position of the bucket tooth tip and its desired position. However, issues such as high loads, large variations in working conditions, and mutual influences of the fluid remain challenging[11].

In trajectory tracking control, Zhang Xinrong and others proposed a variable-domain fuzzy multi-parameter self-tuning PID control method based on the variable-domain concept. They used cubic non-uniform rational B-spline curves in joint space for linear smoothing and fixed-point excavation trajectory planning, obtaining a series of values for the angles, angular velocities, and angular accelerations of each joint during the excavator's motion and performing trajectory tracking control [12]; TIAN J and others combined automatic working face generation technology and cantilever tunnelling error detection techniques to integrate fuzzy neural networks with PID to compensate for pose errors, establishing the body position and cross-section model and performing boundary compensation based on actual cross-section errors, thereby achieving the ideal excavated cross-section shape [13]

Bucket position perception is crucial for precise construction. Based on this, LIN and others established the calculation, analysis, and prediction of the rotation angle of a large remote-controlled excavator during deceleration and braking in a spatial Cartesian coordinate system, using a simplified model of the upper structure of a hydraulic excavator. They derived the formulas for the centre of gravity and moment of inertia of the working device and, combined with the relationship between the hydraulic system and braking torque, estimated the bucket braking stop position[14]. In terms of visual detection, Liu Wenjie and others designed a visual perception module that combines LiDAR and a monocular camera, using Autoware to solve the joint calibration parameters to achieve temporal alignment between the two, employing YOLOv5s to detect bucket images, and utilising point cloud clustering to obtain bucket feature point clouds, thereby deriving the three-dimensional bounding box and current pose of the bucket, completing the detection of the excavator bucket[15].

Functionally, intelligent trajectory control has evolved from single-route following to various semi-automatic operation modes. Liu Jian and others summarised single-hand semi-automatic operation, boom-assisted semi-automatic line operation, and angle-maintained semi-automatic line operation, which have all achieved good results in tasks such as planar excavation, cutting on slopes, and ground levelling, indicating that trajectory control is developing towards 'task functionalisation' [11].

At a higher level, neural network methods are also used for trajectory control. Using DDPG neural networks to develop trajectory controllers enables continuous control of the joint, boom and bucket angles, allowing the bucket teeth to follow a given trajectory and move accordingly. Compared with previous methods that maximised mechanical gain to achieve maximum digging force, this approach focuses more on the ability to complete trajectory tasks and understanding the operator's intent, that is [3], from 'executing trajectories' to 'understanding tasks'

(3)Remote control and immersive interaction

Remote control is currently the type of intelligent technology that is closest to practical engineering applications. Remote control, wireless communication security, collision avoidance, and material recognition are part of excavator intelligent control, while immersive visuals encompass VR/AR integration, 3D spatial perception, low-latency video transmission, panoramic cameras, and real-time simulation prediction. The challenge is not merely to transmit the field situation to a remote location, but to reproduce the scene and operational experience as accurately as possible, giving the operator a sense of being present on site.

Earlier research papers also mentioned the concept of remote control: cameras transmit live images to a distant computer, and technicians use remote controls to operate the PLC for remote operation. Tan Chen pointed out that excavator operations under poor conditions can be somewhat dangerous, and using remote control can greatly improve the operator's labour intensity and safety[5].

In the aspect of automatic weighing, Yu Songsong and others adopted a method combining a boom hydraulic cylinder with pressure monitoring, vehicle body inertial sensors, and speed compensation to achieve automatic detection of the excavator's effective load [16]. This is conducive to accurate loading and the evaluation of work efficiency.

The application of mining has further driven the development of remote control to a certain level. Currently, large mining excavators have achieved remote monitoring and remote control: the former uses 4G or 5G to transmit data to the cloud for PLC data monitoring, operational analysis, and measurement point alarms; the latter employs high-definition cameras, collision-avoidance radars, acceleration sensors, gyroscopes, and other devices to transmit the images, sounds, and vibrations of the construction site to a distant control room, allowing operators to accurately manipulate excavators several kilometres away[7]

From a broader perspective, Wei Jianlong and others have proposed a three-tier intelligent management and control platform for high-end equipment, comprising a multi-sensor fusion collaborative swarm control system, a digital twin and multidimensional data analysis system, and a full lifecycle decision support system for equipment, combined with 5G networks, high-definition video monitoring, personnel positioning, remote control, and various other specialised sensors[17]. This implies that remote operation is no longer a standalone function but an integral part of the platform-based intelligence.

(4)Online monitoring, condition diagnosis and digital twin

Intelligence is not only about achieving automation in the operation process, but it can also be seen, diagnosed, and maintained in the equipment's operating status. Online monitoring, condition diagnosis, and electronic fencing are classified under the category of excavator intelligence technology and are considered to play a significant role in practical engineering [6].

In terms of mining equipment, these technologies are developing rapidly. Based on digital twins and multidimensional data analysis platforms, including equipment condition monitoring, remote control, data storage, data backup, application display, data analysis, system integration, and information sharing, it can be connected with the customer's existing systems, facilitating information flow and collaboration between different departments of the company. This system collects and processes various forms of data such as pressure, temperature, displacement, vibration, video, environmental conditions, and maintenance to ensure good equipment utilisation, uptime, and operational efficiency [17].

Furthermore, the decision support system for the entire lifecycle of equipment elevates intelligence from the device level to the management level. Its main components include online data analysis, intelligent operation and maintenance, asset management, intelligent fault diagnosis, and operational management. It can use current and past information of the equipment to determine its status, performance, and stability, predict imminent component failures, and gradually become intelligent through the continuous recording of faults and solutions [17].

For large mining excavators, online vibration monitoring, regular maintenance, fault self-diagnosis, and combined monitoring by multiple sensors are all part of intelligent systems [7]. By comparing existing data with other related data, it is also possible to anticipate potential future issues, thereby preventing major accidents. Intelligent maintenance methods primarily involve the use of computer control technology, precise sensing technology and GPRS communication technology to collect information, transmit information [18], process information and make decisions, indicating that intelligence encompasses not only production control but also maintenance control.

(5) Neural networks, autonomous navigation and mission-level autonomous operations

Autonomous operation marks a further step towards the intelligentisation of excavators and is currently a focus of research. Neural networks endow excavators with new capabilities; they do not merely replace a single controller but are responsible for tasks such as visual target detection, autonomous navigation, and excavation trajectory throughout the entire autonomous operation process, forming an integrated system. Regarding target input, a target detection method based on the LSTM network has been proposed, which, under supervised conditions, trains operators to focus on moving objects. This enables the system to maintain effective tracking even when the target moves relative to the camera and provides relevant parameters for subsequent autonomous navigation. Compared with traditional visual tracking methods, this approach does not require a specific type of target, increasing the intelligence of visual input. For navigation issues, the DDPG neural network is used to achieve autonomous navigation, enabling the robot to move autonomously based on limited environmental information, its own sensor data, and visual tracking results, while controlling the continuous variables under its command. This approach is more aligned with the excavator's requirements for continuity and precision than methods that discretise the environment and actions [3].

From the perspective of trajectory control, based on DDPG, continuous value control of the boom, stick, and bucket angles can be realised, and any trajectory can be fitted and followed. Intelligent control of excavators is not simply a combination of various individual algorithms but an organic whole, which includes visual tracking, autonomous navigation, and trajectory control, among other components, with information exchange and logical sequencing between them [3]. This helps us to further understand the concept of task-level autonomous operation.

4. TYPICAL APPLICATION SCENARIOS AND ENGINEERING VALUE

From an application perspective, the large-scale implementation of intelligent excavators is most likely to be initially realised in enclosed environments, high-risk working conditions, and highly repetitive operation sites. Intelligent construction machinery has already been applied in enclosed environments such as mines, ports, metallurgical facilities, and rescue operations; however, achieving autonomous construction in open construction sites is still at an early stage [6]. Therefore, the operational environment has a significant impact on the application of advanced intelligent technologies.

Mines are among the most representative application scenarios. In the intelligent construction of large mining excavators, it is already possible to achieve safety protection, monitoring, maintenance, and remote control, and in the future, development will move towards single-machine intelligence and multi-machine collaborative control [7]. For mining enterprises, this is not merely a matter of improving the efficiency of a single machine, but concerns the overall construction of minimally staffed or even unmanned production and intelligent mines.

Based on research work on the WK series excavators, the value of achieving platform-based applications in mining environments has been realised. By integrating a series of functions such as multi-sensor fusion collaborative swarm control, digital twin, multidimensional analysis, and full lifecycle decision-making, excavator intelligence has evolved from single-machine control to encompassing the entire process of production, service, operation, and management [17]. The benefits to clients are improved equipment availability, more effective remote services, faster fault warnings, and greater convenience in their own management and maintenance tasks.

In general construction sites, semi-automatic trajectory control and auxiliary functions such as level grading, slope shaping, and bucket angle maintenance are also very useful. Intelligent trajectory control can significantly reduce the reliance on manual experience, improve work efficiency and project quality while ensuring the safety of workers [11]. Therefore, the intelligence of excavators is not solely about achieving unmanned operation but making the construction process smoother, more reliable, and easier to operate.

5. THE MAIN PROBLEMS CURRENTLY EXISTING

Although the intelligence of excavators has achieved certain results, there is still some way to go before reaching high-level autonomous operation. The biggest problem is the poor robustness of perception in complex environments. Major obstacles include high video transmission latency and insufficient perception accuracy. Environmental perception, immersive vision, and remote operation are issues that need to be addressed. After perception is affected by dust, obstruction, strong light, vibration, or complex backgrounds, subsequent actions will be compromised.

The second issue is the difficulty in modelling dynamics and resistance. During the excavation process, the load varies significantly, and the shape, density, and interactions of the excavated materials are all uncertain. Early research on trajectory control has indicated that excavators are high-order nonlinear systems; furthermore, reviews on intelligent trajectory control have focused more on the impacts of load variations, engine speed changes, and hydraulic system flow on control.

The third issue is poor robustness under different operating conditions. Although methods such as LSTM and DDPG perform well in visual tracking, autonomous navigation, and trajectory control, some scholars have pointed out that visual tracking does not fully take into account motion blur and changes in image scale, indicating that current autonomous operations are still at a relatively low level and cannot guarantee normal operation for extended periods in more complex and unknown environments.

Performance bottlenecks of remote interaction systems. Although remote monitoring and remote operation have been applied in engineering, issues still exist regarding low latency, high reliability, and high realism. Remote systems need to transmit high-definition video streams, collision-avoidance radar data, tilt angles, and vibration information simultaneously, and any problem in any of these aspects can lead to control errors or even safety risks.

In addition, factors such as system construction costs, platform integration difficulties and differing application evaluation standards also pose certain obstacles to intelligent development. For open construction sites, users place greater emphasis on the input-output ratio, and the working conditions are more complex and variable, making the benefits of advanced intelligence far less apparent than in mining scenarios. Therefore, for a period of time, the intelligence of excavators will involve the simultaneous development of technology and application scenarios.

6. DEVELOPMENT TRENDS AND PROSPECTS

From the perspective of future development trends, the integration of data-driven approaches with physical mechanisms is an important direction for the intelligence of excavators. Relying solely on mechanistic models cannot address all operating conditions, while purely data-based methods are limited by the quantity and coverage of training samples. In issues such as visual object detection, autonomous navigation, and trajectory tracking, neural networks and reinforcement learning have been proven to be better choices, and the same applies to complex, continuous, and nonlinear engineering problems.

Fusion of multi-source heterogeneous perception will be further strengthened. Research on three-dimensional vision systems for hydraulic excavators, binocular recognition, as well as the collaboration of vision and radar and multi-sensor arrays all indicate a point: a single sensor cannot ensure long-term stable high-precision construction. In the future, it will be more important to obtain robust, reliable scene descriptions capable of completing designated tasks within the same temporal and spatial coordinates, rather than continuously improving the precision of individual sensors.

Trajectory control will evolve from 'action automation' to 'task automation'. Previous applications such as fuzzy control, genetic algorithms, intelligent trajectory control designed for semi-automation, and arbitrary trajectory control based on DDPG all indicate that the future goal is not only to enable robots to follow trajectories, but also to make robots understand task requirements, perform corresponding actions, and possess a certain level of robustness.

In mining scenarios, cluster collaboration and platform-based operation and maintenance will be more widely applied. Intelligent single-machine operation is the first step, while unified management of multiple devices, remote control, digital twins, health management, and maintenance decision-making will be the core competitive advantages in the next phase. The value generated by the interaction between excavators, mining trucks, drilling rigs, transport vehicles, and related management systems may far exceed the value obtained from optimising a single device.

Intelligent operations and maintenance throughout the entire lifecycle will also evolve from an auxiliary function to a key component. The fundamental technology chain for intelligent maintenance is already clear, and in research on the WK series platforms, this chain has been extended to online analysis, fault knowledge bases, life prediction, spare parts management, and expert online support. In the future, manufacturers will provide not only the equipment itself but also remote diagnostics, online updates, maintenance services, and capabilities supporting digital twins.

7. CONCLUSION

The intelligence of excavators has evolved from the initial partial automation, represented by the hydraulic actuators and work device trajectories, to the current comprehensive level of intelligence, including environmental perception, remote control, trajectory planning, condition monitoring, digital twins, autonomous operations, and group collaboration. Current research suggests that perception, planning, control, and maintenance are not isolated technological modules but form an organic whole centred on completing a specific task. The intelligent design of hydraulic excavators establishes the foundational system architecture, developing a technology for trajectory control that lies between manual and fully automatic operation or enables completely driverless operation. The application of neural networks provides excavators with improved visual tracking, autonomous navigation, and task-level control capabilities, and their use in mining further demonstrates the importance of multi-sensor fusion, remote control, digital twins, and lifecycle management for excavators.

Looking to the future, challenges still exist in aspects such as robustness in complex environmental perception, generalisation capability of control across different working conditions, low-latency and high-reliability interactions, and autonomous operations in open scenarios. However, through the continuous improvement and refinement of data-physical integrated modelling, multi-source perception fusion, task-level autonomous decision-making, swarm collaborative control, and intelligent operation and maintenance services, excavators will gradually evolve from being "assistive and remote-controllable" to "autonomous, collaborative, and evolvable".

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REFERENCES

[1] Cao Youke. A brief study on the intelligent design of hydraulic excavators [J]. Global Market, 2016(35): 225, 227.

[2] Lv Qihui, Wang Lifu. Design and Research on Intelligent Control of Hydraulic Excavator Working Devices[J]. Modern Manufacturing Engineering, 2007(4): 107-109.

[3] Ding Pan, Pang Xiaoping, Chen Jin. Design of an Excavation Robot Visual Tracking System Based on Long Short-Term Memory Networks [J]. Mechanical Manufacturing and Automation, 2019(4): 145-148.

[4] Yu Huiting, Li Li. Intelligent Control System for Hydraulic Excavators[J]. Coal Mine Electromechanics, 2008(5): 31-34.

[5] Tan Chen, Song Weiqi. Research on Intelligent Design of Hydraulic Excavators[J]. Hydraulics and Pneumatics, 2016(9).

[6] Lu Liang, Wu Junkai, Sun Ning, et al. Intelligent Construction—Intelligentisation of Construction Machinery[J]. Hydraulics and Pneumatics, 2022(6): 1-9.

[7] Lian Chunping. Current Status and Development Trends of Intelligence in Large Mining Excavators [J]. Open-pit Mining Technology, 2023, 38(5): 70-73.

[8] Li Guihai. Design and Implementation of Visual Perception Algorithm for Intelligent Excavators [D]. Harbin: Harbin Institute of Technology, 2022: 12-49.

[9] Liu Wusong. Intelligent Mining Excavator Operational Environment Perception Based on 3D Point Cloud [D]. Dalian: Dalian University of Technology, 2022: 39-62.

[10] Xiao Ting, Wen Huaixing, Xia Tian. Intelligent Control System of Excavator Based on Binocular Recognition Technology[J]. Engineering Machinery, 2007(3).

[11] Liu Jian, Li Wenxin. Technical Route and Function Overview of Intelligent Trajectory Control for Excavators[J]. Construction Machinery, 2020(2).

[12] Zhang Xinrong, Kang Long, Tang Jiapeng, et al. Intelligent Excavator Trajectory Tracking Based on Variable Domain Fuzzy Multi-Parameter Self-Tuning PID Control[J]. China Journal of Highway and Transport, 2023, 36(2): 240-250.

[13] TIAN J, LIU Z J, ZHU W J, et al. Fuzzy rule-based section forming for mining robotic excavation error compensation[J]. IEEE Access, 2023, 11.

[14] LIN Y T, XIONG J Q, ZHU W L, et al. Research on the Prediction Method of Braking Rotation Angle for Remote-Controlled Excavator[J]. Sensors, 2023, 23(15).

[15] Liu Wenjie. Research on Vision-Based Intelligent Detection and Control Technology of Excavator Buckets[D]. Xuzhou: China University of Mining and Technology, 2023: 39-87.

[16] Yu Songsong, Liu Jian. Intelligent measurement system for effective load of hydraulic excavators [J]. Construction Machinery, 2023, 54(4): 54-57.

[17] Wei Jianlong. Research and Application of Intelligent Cluster Technology for WK Series Excavators[J]. Mechanical Engineering and Automation, 2024(3): 215-216.

[18] Zhang Zhe. Research on Intelligent Maintenance Application of Large Mining Shovel Excavators [J]. Southern Agricultural Machinery, 2019(8): 28.