

Technological Advances and Engineering Applications of Integrated Cleaning and Inspection for Oil and Gas Pipelines

Yuxin Nie¹ Jingyi Zhou¹ Jiamei Cai² Yan Fang¹ Chenbo Yang¹ Zhuowei Chen³
Tianyi Wang³ Manyi Li¹

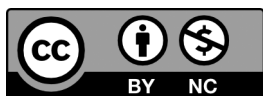
1.School of Petroleum and Natural Gas Engineering, Chongqing University of Science and Technology, Chongqing;

2.Chongqing University of Science & Technology, College of Chemistry and Chemical Engineering, Chongqing;

3.Chongqing University of Science & Technology, School of Mechanical and Intelligent Manufacturing, Chongqing

Abstract: The transfer of oil and gas resources towards high-risk and high-intensity directions has put forward higher environmental requirements for long-distance oil and gas pipelines, as well as higher demands for operation and maintenance efficiency and safety. Frequent, scattered, bloated and inefficient cleaning and detection operation processes are not conducive to the improvement of intelligent pipeline integrity management systems. This paper studies an intelligent maintenance system integrating cleaning, detection and data. This system is based on a modular concept, adopts multi-modal non-destructive testing technology and a high-performance and efficient edge computing framework, and is an intelligent system integrating structural adaptation, collaboration and data integration. Typical pipeline network field verification. This system has significant advantages in operation efficiency, defect detection accuracy, and data closed-loop management, and has good engineering promotion and application value. It provides a method and technical means for efficient, safe, and intelligent operation and maintenance of long-distance oil and gas pipelines.

Key words: Oil and gas; Pipelines; Integrated cleaning and inspection; Modular and design; Multimodal and detection; Edge computing



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1 Introduction

In the context of the optimization of the national energy structure and the deepening of the strategic deployment of oil and gas resources, the integrity management of long-distance oil and gas pipelines, as a key channel for the efficient transmission of energy, has become an important link in enhancing the level of national energy security, but due to the longer and longer operation of the national pipeline, a variety of problems have arisen in its service, such as corrosion

Corresponding author: Yuxin Nie, School of Petroleum and Natural Gas Engineering, Chongqing University of Science and Technology, student.

Article Citation: Nie, Y. X., Zhou, J. Y., Cai, J. M., Fang, Y., Yang, C. B., Chen, Z. W., Wang, T. Y., Li, M.Y.(2025). Technological Advances and Engineering Applications of Integrated Cleaning and Inspection for Oil and Gas Pipelines. *Environment and Resource*, 7(2), 379-388.

inside the pipeline, hydrate deposition, weld defects, and other phenomena continue to aggravate. It seriously affects the oil and gas pipeline's oil transmission efficiency, and even forms major safety hazards, so how to realize efficient, intelligent, integrated oil and gas pipeline operation and maintenance management technology is a core topic that must be solved.

The traditional pipe-cleaning detection(Li R, 2024) is a serial form of operation. After a number of operation deliveries and operation of the switching work, there will be a long operating time, low synergy efficiency, data flow cuts and other problems, which can not realize the requirements of intelligent management of ultra-large-scale pipeline network. In recent years, with the development of intelligent sensing, small electronic systems and data fusion technology, the concept of integrated cleaning and inspection has gradually emerged as an important direction for the transformation and upgrading of pipeline operation and maintenance technology.

This study focuses on the system demand of “cleaning+detection+data processing” of long-distance pipeline, proposes a comprehensive solution with modularized structure, self-adaptive ability and high data intelligence, and builds a closed-loop system of structural integration--data retrieval--intelligent diagnosis. The closed-loop system of intelligent diagnosis is constructed, and the cutting-edge and engineering application value of the technology is verified through field application, which will provide comprehensive technical solutions and technical support for the intelligent management of oil and gas pipelines throughout their life cycle.

2 Technical Solution and Implementation Framework

2.1 Technical Solution and Implementation Framework

In order to solve the problems of incoherent cleaning and inspection processes, low operational efficiency and insufficient intelligence in the operation and maintenance of long-distance pipeline systems, this paper proposes a data-driven integrated cleaning and inspection system based on modular design concepts and integrating multimodal sensing and edge intelligence. The system realizes the fundamental change of operation process from “series connection” to “parallel connection” by means of the three-in-one design concepts of structural integration, functional synergy, and intelligent operation and maintenance, and supports the efficient, safe, and autonomous operation of long-distance pipelines under complex working conditions. This chapter elaborates systematically on three aspects: overall system architecture, key subsystem design and operation process standards.

The overall architecture of the integrated system is a three-layer coupled architecture, which is divided into a physical execution module, a detection and sensing module and an intelligent decision-making module. The three modules are seamlessly connected to each other through a unified control bus and the management of data flow, forming a closed loop of cleaning-detection-analysis.

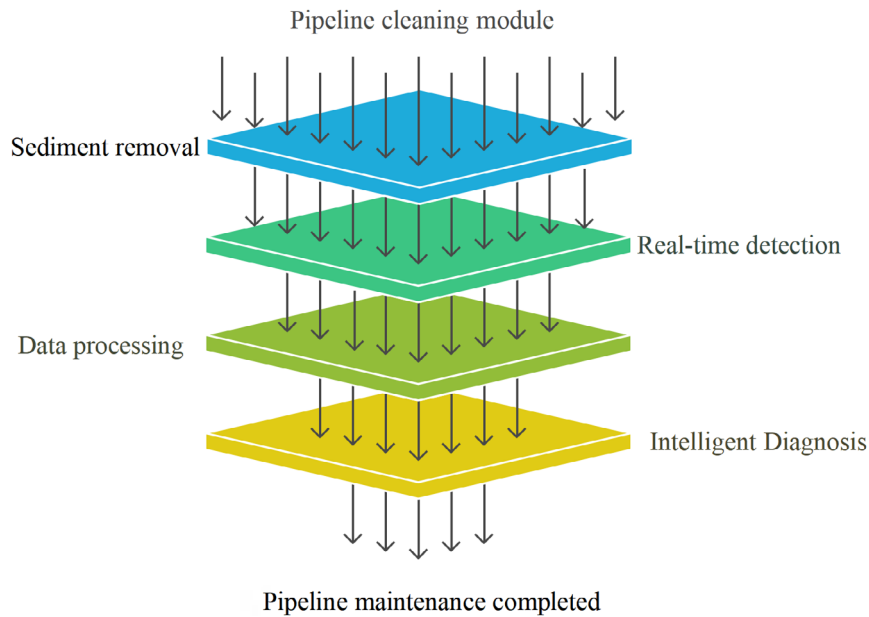


Figure 1 Duct cleaning and inspection process

The cleaning module is deployed at the front of the unit, using a high-strength adjustable brush set and a multi-nozzle fluid flushing unit, relying on high-pressure differential propulsion to realize the efficient removal of deposits on the inner wall of the pipe, such as wax scale, hydrates, corrosion products and other things. The overall structure of the module has the ability to adjust elastically, according to the diameter of the pipe, real-time expansion and contraction, to ensure that the coverage and contact are more stable, the cleaning range and the actual results are more stable and reliable. Some of the pipes that have been used have cracks on the surface or the coating is peeling off, in which case the cleaning strength will be responded to by intelligent feedback algorithms to avoid secondary damage.

The back of the cleaning unit is arranged with a multi-mode data acquisition capability of the detection module. Integrated magnetic leakage (Yang L J et al., 2024) detection (MFL), ultrasonic detection (UT), eddy current testing (ECT) and other different nondestructive testing(Huang S T & Jia X L, 2024) sensor array, the use of pluggable interfaces between modules, applicable to different combinations of working conditions, all the detection data real-time uploaded to the data processing module, through the edge computing platform for pre-processing, feature extraction and initial identification, and then compressed and uploaded to the cloud platform or The data is then compressed and uploaded to the cloud platform or expert system for the next step of intelligent diagnosis and visualization analysis.

In order to improve the adaptability to working conditions and flexible deployment ability of the system, the hardware deployment of the platform adopts the flexible coupling deployment mode, which supports the automatic adaptation of different pipe diameters ($\Phi 300\text{mm}-\Phi 1200\text{mm}$) in multi-specification pipe diameters and multi-category working conditions, and possesses strong obstacle-crossing ability and stability of the diameter, which is suitable for the operation of high passing efficiency under the special working conditions of changing slopes, high differences, sharp curves, and serious wax accumulation conditions. It is suitable for special working conditions such as change of slope, high difference, sharp curve, serious wax accumulation and so on.

2.2 Key Subsystem Design

2.2.1 Adaptive Structure and Power Unit Integration

The fundamental support mechanism of the system is completed by the modular slide rail and the electronically controlled elastic arm structure, with adaptive dynamic response characteristics, the main structure can sense the change of the pipe diameter, and according to the resistance, pressure real-time feedback data to adjust the support point and wheel pressure parameters, so as to maintain the stability of the center of the equipment, to ensure the accuracy of wall-to-wall detection, in the process of cleaning and detection of the two modules between the mechanical vibration isolation. In this process, mechanical vibration isolation is used between the two modules of cleaning and detection to decouple the system, so as not to affect the vibration wave generated by high-frequency brushing and washing of the non-destructive testing process (Wu J & Li Y, 2021) waveforms, and to improve the signal-to-noise ratio and interpretation accuracy.

The power system adopts a distributed propulsion mode, a multi-axis electronically controlled drive system, an inertial navigation module, and does not rely on the fluid pressure difference thrust, with controllable speed adjustment ability, and a maximum forward speed of 0.35m/s. In order to ensure that the equipment can work normally in extremely harsh (high temperature, high humidity, high pressure) environments, the packaging of the drive mechanism and the energy supply system adopts corrosion-resistant insulating composites, and adopts an internal circulation cooling device.

2.2.2 Multi-modal Cooperative Perception and Defect Recognition Mechanism

Because there are many types of defects inside oil and gas pipelines, one sensor cannot cover all possible faults, so three commonly used NDT technologies are added inside the detection module, leakage detection technology (Hao D Y et al., 2022) can effectively identify wall corrosion, perforation and crack defects, applicable to the middle and deep diagnosis of carbon steel and alloy materials; ultrasonic detection (Xue J H et al., 2021) provides high-precision geometric parameter determination, which is mainly used for accurate judgment of the depth and length of defects, etc., applicable to the quality of weld seams and the determination of interlayer peeling; eddy current detection is mainly applicable to the surface layer of micro-cracks, coating peeling and hardening degradation zone, with high-frequency sensitive response.

Various types of sensor data are synchronously collected by the embedded processor and pre-processed by timing calibration, waveform analysis and map fitting. The back-end algorithm uses a convolutional neural network (CNN) (Zhong M S et al., 2023) to extract multi-dimensional feature vectors and combines with a fusion decision model (FusionNet) for feature coupling and pattern classification. Experiments show that the model has an average correct rate of more than 93% in multi-class typical defect recognition (Huang S T & Jia X L, 2024), which greatly improves the overall recognition capability of the system.

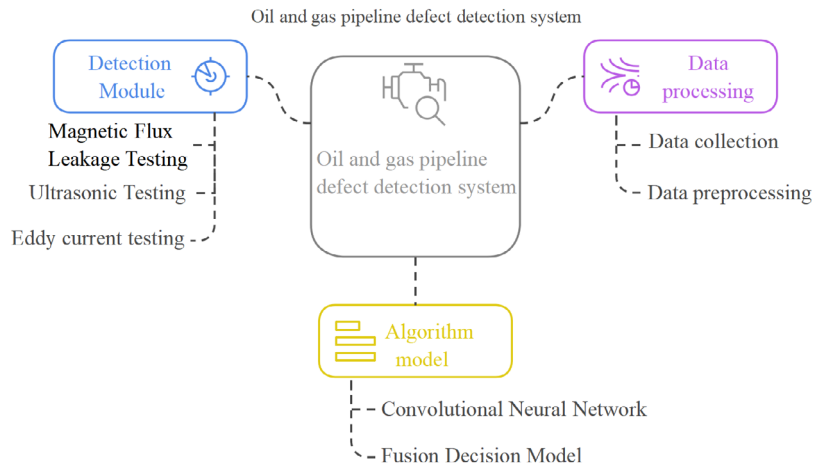


Figure 2 Oil and gas pipeline defect detection system

2.2.3 Edge Intelligence Platform and Remote Linkage System

In order to realize the real-time processing and transmission optimization of high-dimensional data, the system integrates ARM+FPGA(Xu Y, 2023) heterogeneous computing edge intelligence unit, the platform can support ultra-high floating-point processing, the processing rate reaches trillions of levels, especially in the multi-channel image, vibration, and magnetic signals co-recognition with parallel acceleration advantages. The data processing link uses a three-stage intelligent(Wang Y Q et al., 2023) pipeline for data noise reduction, feature dimensionality reduction, and anomaly detection, and can compress the data to a maximum of 15 : 1, reducing the burden of remote communication.

The communication system uses industrial-grade 5G+Cat.M1 dual-mode design, combined with MIMO links and network slicing technology, to achieve ultra-low latency communication of less than 20 ms. The system supports the 5G URLLC mechanism, and with the expert system, it can complete major fault reporting and response within 300 ms. The platform cooperates with the remote AR consultation system, and the technicians can realize cross-region, cross-level remote collaborative diagnosis through holographic image interaction and visualization data overlay.

2.3 Operational Process Design and Implementation Path

In order to ensure that the system can be efficiently deployed and operated under various working condition scenarios, the operation process is designed as a standard, iterative five-stage closed-loop system. Firstly, the environmental prediction and task configuration stage utilizes GIS and the existing historical pipeline database to do working condition analysis(Wu S, 2023), automatically matches the combination of equipment modules and parameter settings, and then goes through the assembly of equipment, functional tuning, and on-site functional testing to ensure the best results before the deployment of the system.

Formal operation, the system adopts the cleaning - detection of parallel way into the pipeline operation, and the system through the inertial navigation and odometer accurate positioning, the whole monitoring platform can be real-time monitoring to the location of the equipment, monitoring the operation of the equipment and equipment to screen out the defects of the initial screening results can be realized in the process of the operation of the dynamic scheduling, dynamic re-planning of the path. After the job is completed, the system automatically performs self-test recovery

operations, automatically generates data reports and completes the closed-loop upload to the cloud, entering the defect evolution modeling, generating repair work orders.

This process is designed to make the system's work process flexible and adaptable, taking advantage of long distances, high drop-offs, and frequent changes in pipe diameter, and can be quickly set up and used multiple times, thus reducing the cost of each job.

3 Engineering Practice and Application Effectiveness

3.1 Engineering Application and Performance Evaluation

In order to verify the reliability, detection accuracy and operation economy of the integrated cleaning and inspection system designed in this paper, a large oil and gas field in the central and western part of China is selected for the application test and technical evaluation of the system, and the system test and analysis is carried out on a representative long-distance oil and gas pipeline section with large caliber, multiple geomorphology and multiple working conditions to systematically analyze and study the relevant data in terms of the system accessibility, the effect of the system defect identification, the effect of remote interaction, and the system operation cost. Systematic analysis and research of the relevant data of the integrated cleaning and inspection system in terms of system accessibility, system defect identification effect, remote interaction effect and system operation cost. Through the whole process of data collection and comparative analysis of typical tasks, the feasibility of engineering application and technological advancement of the integrated cleaning and inspection system are analyzed in an all-around way.

The test object is distributed in the plains and hills and tundra environment of three sections of different environments of the typical service pipe, the total length of nearly 85km, the pipeline specifications were $\Phi 406\text{mm}$, $\Phi 508\text{mm}$, $\Phi 610\text{mm}$, the internal deposits and corrosion degree of the differences in the typicality of each section of the pipeline has been more than 15 years of service, and from the past history of operation and maintenance data can be found to have a varying degree of wax buildup, Weld defects(Fan X L et al., 2025) and pipeline deformation and other failure risks can be found from the past historical operation and maintenance data, which is suitable for the integrated system performance verification site.

Before the test, based on the past GIS data of each section and the inspection test archive, digital modeling and risk assessment of the operation section are carried out to guide the combination of modules, parameter setting and optimization of the operation process. Each section of the operation has to go through a unified tuning process to ensure the matching and repeatability of the system. During the implementation process, inertial navigation and laser positioning means are used to capture the trajectory information, so as to obtain the displacement-stress mapping curve of the whole process, which is used for evaluating the stability of the passage of the equipment and the closed-loop ability of the feedback.

3.2 Field Performance and Stability Analysis

System in the three sections of the field operation process are a successful delivery, recovery operations, without any jamming, wire, signal interruption and other faults, equipment in the bending radius as small as $1.5D$ (where D

represents the diameter of the pipe), the maximum longitudinal slope of up to 12° of the complex section has shown good stability and through the flexible module coupling structure and support self-adjustment algorithms to deal with the diameter of the section so that the center of the equipment to stabilize the deviation $< 3\text{mm}$, to ensure that the cleaning brush group and the detection probe close to the wall. 3mm , to ensure that the cleaning brush group and the detection probe are in contact with the wall.

The measured running speed is stabilized in the range of $0.25\text{-}0.32\text{m/s}$, and the dynamic adjustment function of the cleaning force effectively suppresses the slippage and stagnation in the high wax section. The system completes the cleaning, testing and data analysis process at one time, thus greatly shortening the traditional serial time of pipe cleaning and testing. Under some harsh environments, the edge processing platform of the system has been running continuously for more than 9 hours, and the data transmission rate has been maintained at more than 99.2% , which proves that this device has good adaptability to working conditions and continuous work performance.

3.3 Defect Recognition Capability and Assessment Accuracy

In the process of operational testing and inspection, a total of 421 suspected defects detected, after the metallographic excavation and three-dimensional laser reconstruction and phased array ultrasound(Zhao X & Wang Z W, 2025) retesting, a total of 284 corrosion defects identified, crack defects 57, the rest of the wall thinning, weld defects and other types of defects, the identification of the effectiveness of the results (compared to the results of the standard validation) of 92.6% , in the whole The identification effect (relative to the standard validation results) is 92.6% , which is higher than the 90% detection rate standard in the whole pipe section inspected, and has good stability and versatility.

The spatial distribution of defects shows the evolution mechanism of key risk segments. From the statistical data, more than 75% of the defects are concentrated in the heat-affected zone (HAZ) of the inner elbow and the circumferential weld, and there is a high degree of consistency between this characteristic distribution and the distribution map of the stress concentration factor (SCF) constructed based on the finite-element method, with a correlation coefficient of 0.82 ($p < 0.01$). This indicates that the system has the ability to accurately recognize the risky region of a high-stress field.

In addition, based on the defect life cycle database constructed by the system and combined with 8-year historical inspection data and GIS geographic information, a defect trend prediction model based on spatio-temporal convolutional network(Li Y H & Tao Y, 2025) (STCNet) is trained, which takes feature scale, time scale, and spatial neighborhood as the input variables, and through which the evolutionary trajectories and evolutionary rates of different defect types are fitted to the typical In a typical X70 steel pipe section, two corrosion penetration defects with depths greater than 65% of the pipe wall thickness are successfully predicted 6 months in advance, which is significantly better than previous empirical methods and cycle assessment models.

The system automatically forms a defect report in standard format, containing 18 main indexes such as defect appearance, residual strength, safety margin, repair priority, etc. It has the ability to output strength decay curves in accordance with the DNV-RP-F101 standard, and is tightly integrated with the pipeline asset management system (EAM) to achieve the digital management of the whole process of inspection-diagnosis-maintenance.

3.4 Improvement of Operational Efficiency and Economic Analysis in the Comprehensive

Integrated operating system comprehensive comparison analysis under the operational efficiency and cost control

has a greater advantage, the average single-segment operating time compared to traditional methods to reduce about 40.7%, personnel input reduced by 35.2%, the number of times the equipment delivery is reduced by half, the operation of the valve operation, the scene waiting for the operation of inefficient operational phenomena such as reduction. Moreover, since the data collection is performed at the same time as the cleaning operation, the problem of repeated operations is reduced, and the phenomenon of inconsistency in the collected data is avoided, thus reducing the number of manual reviews and the errors generated during the review.

Economic calculations show that after the deployment, the operation cost for an operation unit is reduced by 26.8%, which mainly saves indirect losses from manpower, transportation, equipment maintenance and operation delays, and after the operation, the defective work order generated by the system is linked with the GIS model(Chen H, 2025) , which supports remote diagnosis and advance scheduling of maintenance tasks, which reduces the rate of downtime due to accidents to 37% in the operation, and the maintenance response time in the operation is also reduced to 37%. The maintenance response time is also extended to 48 hours, which improves the efficiency of operation and maintenance and makes the resource deployment more reasonable.

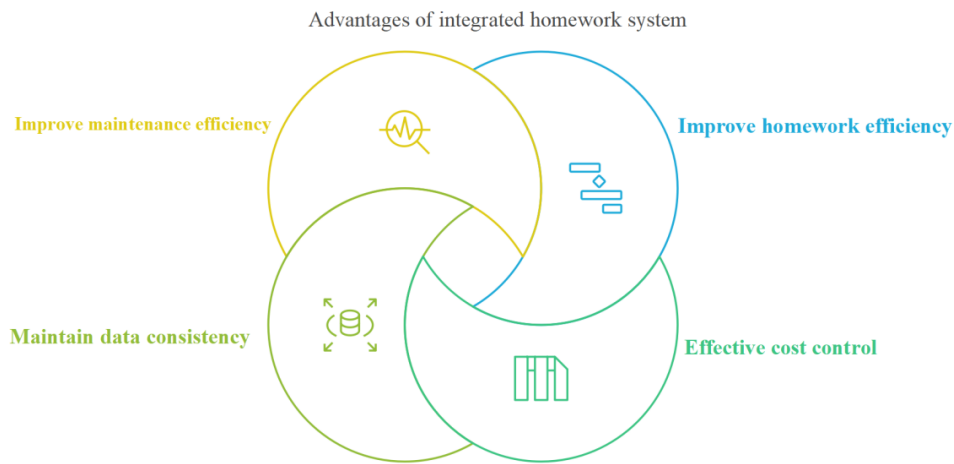


Figure 3 Advantages of integrated homework system

Overall, the system not only achieves high engineering standards in terms of operational stability and detection accuracy, but also shows obvious engineering advantages in terms of efficiency improvement and economic control, which verifies its wide applicability and promotion potential in large-scale pipeline network intelligent operation and maintenance.

4 Conclusion and Future Outlook

Aiming at the core demand for an integrated, high-efficiency detection and cleaning system in the context of intelligent operation and maintenance of oil and gas long-distance pipelines, we design and realize an integrated cleaning operation platform that integrates cleaning, detection and intelligent data processing. Through modular structure design, sensing information fusion and edge computing platform integration, the system constructs an operation platform with high environmental adaptability, autonomous sensing capability and closed-loop data-driven features, breaking the technical shackles of complicated redundancy and lagging response of conventional phased operation and maintenance

technology.

From the perspective of system function and technology implementation, this study innovatively integrates the high-performance cleaning mechanism and multimodal non-destructive testing technology into a single platform, and achieves real-time coupling and intelligent collaboration of cleaning-inspection-analysis operation processes through adaptive structure adjustment and intelligent data transmission. Field experiments show that the system is able to operate stably in a number of typical complex conditions, with a 100% equipment access rate, an average cleaning efficiency of more than 93%, and a defect recognition accuracy of 92.6%. In terms of defect trend prediction, the established spatio-temporal convolution model has the ability to provide early warning several months in advance, which significantly improves the foresight and scientific nature of operation and maintenance decision-making. At the same time, through the deep integration with the enterprise asset management system, the program builds a digital closed-loop chain of “inspection-diagnosis-maintenance”, which effectively promotes the systematic upgrading of pipeline integrity management.

Although the current research has achieved some milestones, it still needs to continue to expand the general scope of application in extreme working conditions, the resolution of micro-defect identification, and the intelligent prediction of the whole life cycle. Subsequent research can continue to go further along this direction, including improving the reliability, stability and safety of the system for extreme working conditions, developing new materials and energy-saving propulsion systems for high temperature and high pressure, corrosive media and ultra-long-distance working conditions; introducing multi-source perception fusion mechanisms, such as the combination of visual inspection, acoustic emission monitoring and high-frequency electromagnetic analysis, to improve the response of the system for micro-scale and multi-type defects. Sensitivity of the system to micro-scale and multi-type defects; establish self-supervised learning models and continuous learning models to enhance the system’s adaptability and self-evolutionary ability to new defect modes while guaranteeing the model’s generalization ability; strengthen the integration and linkage of the remote expert system and the cloud-based intelligent scheduling platform, and realize the decision-making of operation and maintenance across regions and sites; strengthen the formulation and specification of the industry standards, and build up a complete set of technical systems covering design, inspection, evaluation and operation and maintenance to accelerate the industrialization and popularization of this technology. Accelerate the industrialization and promotion of the technology and regional application.

In summary, the integrated cleaning and inspection system designed in this paper not only theoretically improves the core framework of the intelligent operation and maintenance system at the level of “operation integration”, but also demonstrates its significant advantages in terms of more efficient operation, identification accuracy, operation and maintenance decision-making timeliness and economy from the perspective of engineering practice. The gradual improvement and application of this system is a solid step towards more intelligent and cooperative perception and control, as well as prediction and maintenance of various oil and gas transmission infrastructures in China, which is of strategic significance for the construction of an intrinsically safe, highly efficient and cooperative, and intelligent decision-making energy channel system.

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