PERSPECTIVE

# The Application Prospects of Embodied Intelligence in Oil and Gas Field Laboratories

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## Abstract

**Oil and gas testing laboratories have long encountered structural challenges including unclear functional roles, the disconnection between research and testing, and ongoing talent attrition, necessitating an intelligent transformation. Embodied intelligence, as an emerging paradigm integrating AI and robotics, features a local inference model of "cloud-device collaboration" that overcomes the limitations of traditional AI detached from the physical environment. Embodied intelligence enables laboratories to transition from "passive testing" to "proactive, intelligence-driven operations". Nonetheless, current deployment remains constrained by high costs and limited technological maturity. A phased, pilot-first implementation strategy is therefore recommended, prioritizing application validation in scenarios such as repetitive testing and high-risk operations. On this basis, the AI-driven "One-Person Laboratory" (OPL)—as a concrete manifestation of the "one-person company" concept within the scientific research domain—is expected to foster a new ecosystem of smart laboratories characterized by human-AI collaboration and complementary strengths, serving as a powerful supplement to the existing research system.**

**Keywords**: laboratory, embodied intelligence, analytical testing, application prospects, challenges.

## 1 Introduction

In recent years, artificial intelligence (AI), with its powerful capability to process large-scale of data, has demonstrated substantial effectiveness in automated decision-making, predictive analytics, and process optimization. In the oil and gas industry, AI has been extensively integrated into daily production operations: from seismic data interpretation and revealing subsurface reservoir characteristics [1–4], to equipment fault prediction and engineering parameter

**Submitted:** 17 April 2026
**Accepted:** 12 May 2026
**Published:** 09 June 2026

**Vol.** 2, **No.** 3, 2026.
10.62762/JGEE.2026.553515

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**Citation**
Kang, Q., He, J., Tian, X., Yao, H., Tang, R., Tan, J., & Yang, H. (2026). The Application Prospects of Embodied Intelligence in Oil and Gas Field Laboratories. *Journal of Geo-Energy and Environment*, 2(3), 178–184.

optimization [5], and further to distributed fiber-optic temperature measurement [6, 7] and pipeline leak monitoring [8] — all of which demonstrate its practical value. The mature application of Industry 4.0 technologies (such as autonomous robots, augmented reality, the Internet of Things, and cloud computing) in monitoring oil and gas pipelines in Tanzania further illustrates that the integration of AI with oil and gas operations has shifted from "optional" to "essential" [9, 10]. The digital and intelligent transformation of the oil and gas industry has become a clear trend [11].

In the field of testing and detection, intelligent technologies have also achieved advancement. For example, intelligent rock identification technology has revolutionized the traditional working mode of thin-section analysis, significantly improving both efficiency and objectivity [12]; Unmanned Underwater Vehicles (UUVs) have enabled autonomous inspection, maintenance, and repair in subsea oil and gas operations, providing a new architecture for automated solutions [13]. These advances indicate that the deep integration of artificial intelligence and robotics has already established a solid practical foundation [14].

The year 2024 has been called the "first year of humanoid robots," as AI and robotics technologies have become increasingly integrated. In the spring of 2025, the Government Work Report explicitly proposed, for the first time, "cultivating future industries such as embodied intelligence," marking the elevation of embodied intelligence to a national strategy. The term "embodied" refers to equipping a machine with a physical form that enables interaction with the real world [15]. Embodied intelligence breaks through the limitations of traditional AI, which is characterized as "abstract computation detached from the physical world." Instead of relying solely on human-annotated datasets, it emphasizes perception-decision-action capabilities, and act in complex environments, thereby achieving a deep integration of cognition and physical action [16]. At the same time, edge computing performs on-device processing near the data source, overcoming the high latency and high bandwidth consumption of cloud computing [17–19]; the "device-cloud collaborative" model enables embodied intelligence to handle tasks with high requirements for real-time performance and privacy [20–23]. These technological developments provide a promising pathway for addressing repetitive tasks in complex oil and gas laboratory scenarios, as shown in Figure 1. This paper provides a systematic analysis of the challenges and application prospects of embodied intelligence in oil and gas laboratories, and proposes a conceptual framework (OPL) for future development.

## 2 The Dilemmas of Oil and Gas Field Laboratories and the Advantages of Embodied Intelligence

Over their long period of development, oil and gas field laboratories have developed three structural dilemmas [24]. First, analytical testing is often positioned as the primary task. Many laboratories are often reduced to "assay offices" or testing workshops, and their core identity—engaging in technological innovation, integrating into core business operations, and exploring unknown frontiers—has not been adequately recognized. Second, the functions of research and testing have not been effectively separated. Laboratory researchers are occupied by a large number of mechanical, repetitive testing tasks, making it difficult for them to focus on in-depth scientific research and technological innovation. Third, there are significant challenges in building a skilled workforce. Laboratory personnel lack smooth career progression channels for technical growth, and the pathways for professional title and rank advancement are limited, leading to a serious loss of highly skilled technical talent. Affected by these issues, research in oil and gas field laboratories largely remains at the applied level, rarely touching upon original innovation, making it difficult to achieve disruptive technological breakthroughs.

To improve efficiency, oil and gas laboratories have already implemented some automation projects, such as industrial-scale applications of pretreatment processes including shale gas content determination, liquid saturation porosity measurement, and clay separation [25, 26]. However, this automation is primarily designed for fixed workflows and lacks mechanisms for dynamic feedback and adjustment in response to complex situations. Existing intelligent thin-section identification technology relies on supervised learning and has not yet achieved robust visual understanding of real-world environments [12].

Embodied intelligence offers a different solution. As surveyed in the embodied AI literature [15], embodied intelligence must possess three core capabilities: environmental interaction and task planning, cross-scenario and cross-task generalization, and the developmental and evolutionary capacity for perception and action. Advances in model-based

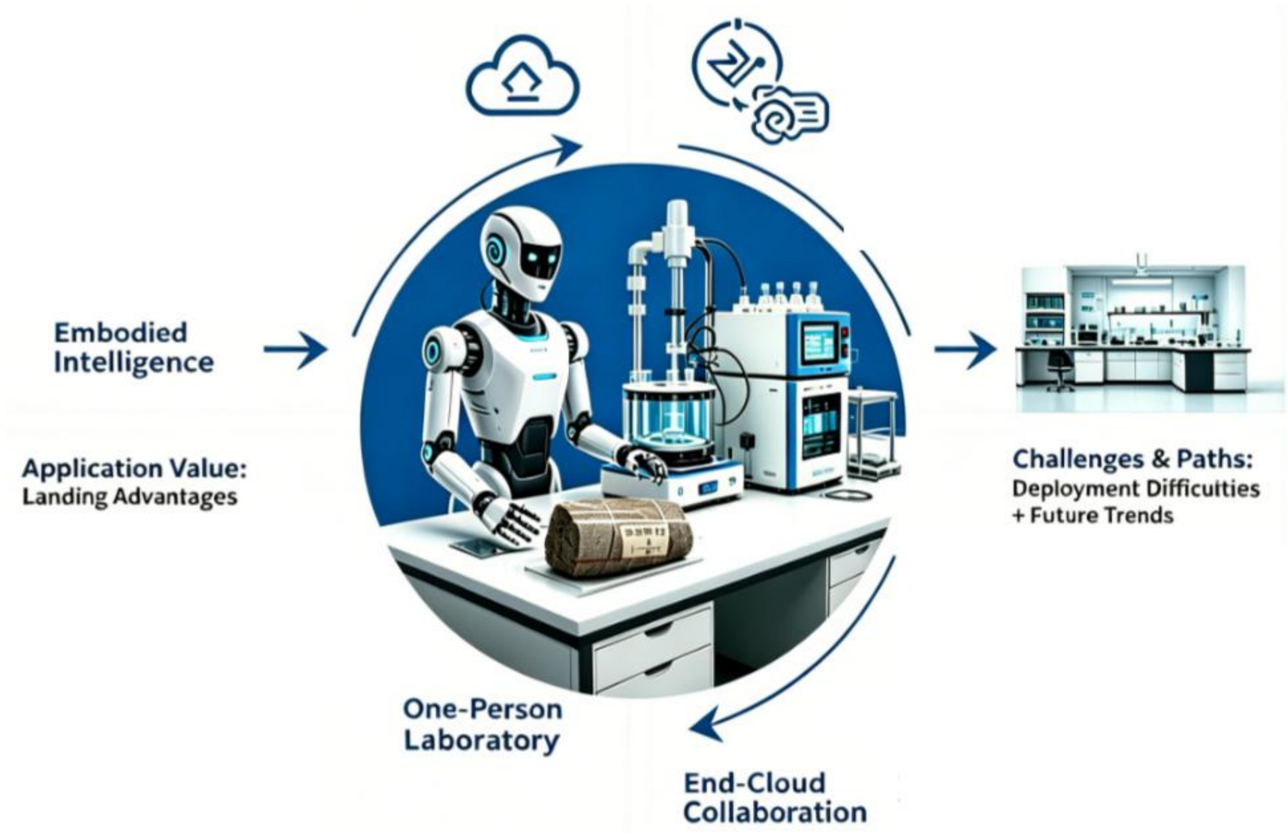


**Figure 1.** The application framework of embodied intelligence in oil and gas field laboratories.

reinforcement learning — including adaptive strategies for determining when to update an agent's world model under real-world constraints [16] — provide foundational algorithmic support for realising these capabilities in complex environments. These characteristics are highly aligned with the transformation needs of oil and gas field laboratories. If successfully promoted and applied, embodied intelligence is expected to bring breakthroughs in the following aspects: First, liberating human labor and promoting the separation of functions. Embodied agents can undertake repetitive tasks such as sample pretreatment, instrument operation, and data acquisition, allowing researchers to focus on fundamental research and original innovation. Second, achieving 24/7 continuous autonomous testing, free from the effects of human fatigue and operational errors, significantly improving efficiency and data consistency, while alleviating the challenges of an aging and understaffed workforce. Third, enhancing the sense of fulfillment among laboratory personnel. Support staff who previously performed mechanically repetitive work can redirect their efforts toward more valuable tasks, avoiding the professional frustration of "giving much but receiving little." Under the industry-wide trend toward oil and gas companies to pursue "low cost, high quality" development, the introduction of embodied intelligence is expected to drive the transformation of testing laboratories from "passive detection" to "proactive, intelligence-driven operations". In the future, beyond significantly improving work efficiency, embodied intelligence technology can also prevent errors caused by declining attention due to heavy workloads, and can replace laboratory personnel in toxic or hazardous positions, thereby reducing potential quality, safety, and environmental risks.

## 3 Discussion for the Deployment of Embodied Intelligence

China's oil and gas laboratories are currently in a critical period of transitioning from "testing support" to "innovation leadership" [24]. Embodied intelligence technology, with its advantages of automation, intelligence, and multidisciplinary integration, offers a potential technical pathway for this transformation. However, high investment costs represent an unavoidable real-world challenge.

The cost structure of an embodied intelligence system can be divided into two levels:

(1) Hardware costs: The price range for humanoid

robots is highly variable, from entry-level systems to high-cost platforms exceeding one million yuan, with the core difference lying in key components such as "dexterous hands." A domestic entry-level dexterous hand can be as low as 3,999 yuan (e.g., Lingxin Lite O6 Lite), while a single dexterous hand capable of precise manipulation, such as that on Tesla's Optimus, costs over 43,000 RMB (approximately $6,000 USD, based on the 2025 exchange rate). The dexterous hand typically accounts for 20% of the entire robot's manufacturing cost, and over 30% of the motion system's cost. Complete humanoid robots range from entry-level products costing just over 9,000 yuan to high-end models priced at the million-yuan level.

(2) Training costs: "Teaching" a robot to work is substantially more expensive than hardware manufacturing and constitutes the primary industrial bottleneck. Every seemingly simple action requires tens of thousands of training trials. For example, "learning to pick up a cup" may require thousands of hours of training data. The cost of collecting high-quality real-robot operation data can be as high as 20 RMB per samples; a trainer working eight hours a day may generate only 2-3 hours of high-quality training data. More importantly, each time the robot enters a new application scenario, development and training must start from scratch. This repetitive development model is costly—a company might need to invest 1 million RMB to develop a single task-specific application. Oil and gas enterprise testing laboratories have dozens or even hundreds of testing items, each with relatively independent workflows. The initial cost of training a robot may therefore be higher than the cost of training a technician and paying their salary for multiple years.

Consequently, the widespread deployment of embodied intelligence in oil and gas testing laboratories will still need to wait for an industry cost inflection point. This inflection point is expected to rely on large-scale production, breakthroughs in progress toward artificial general intelligence (AGI), or new business models. By that time, humanoid robots will no longer be mere exhibits in laboratories but will become an independent industry, accelerating their entry into real-world scenarios such as industrial and service sectors.

## 4 Systemic Challenges Facing the Application of Embodied Intelligence

Beyond cost, the widespread application of embodied intelligence in laboratories currently faces five systemic challenges:

First, the maturity and applicability of the technology remain to be verified: Oil and gas laboratories involve multiphase samples (gas, liquid, solid) as well as special conditions such as high temperature and high pressure. The adaptability, stability, and reliability of existing embodied intelligence technologies still require thorough validation, and mature industry solutions are lacking. Beyond standardized procedures, laboratory work often involves "experience" and "tips" that are difficult to formalize. Whether embodied intelligence will necessarily outperform experienced personnel remains to be determined.

Second, the transformation of the talent structure is difficult: The introduction of embodied intelligence requires technical professionals with interdisciplinary backgrounds in robotics, artificial intelligence, and automation control. However, the current knowledge structure of laboratory personnel is relatively narrow, presenting structural challenges in recruitment and training.

Third, autonomy and safety must be carefully balanced: The laboratory environment demands extremely high operational precision and safety. Embodied intelligent agents may exhibit misjudgments or abnormal behaviors during autonomous decision-making. How to ensure operational safety while maintaining autonomy is a critical technical challenge that urgently needs to be addressed.

Fourth, there is insufficient organizational management and institutional adaptation: Existing laboratory management systems, performance evaluation frameworks, and resource allocation methods are primarily designed around "humans." There is a lack of corresponding management norms, safety standards, and performance evaluation mechanisms for the introduction of embodied intelligent agents. For example, the relevant management regulations for CMA laboratory qualification accreditation also need to be updated accordingly. Institutional lags may constrain the large-scale application of the technology.

Fifth, R&D control and the risk of technological dependency: Key core technologies must be self-developed [24]. If embodied intelligence systems become overly dependent on external suppliers, the laboratory's core capabilities may become constrained by others, contradicting the development philosophy of "firmly grasping the lifeline." Significant technological advantages may trigger a cycle of "overreliance on intelligent systems may erode human expertise and independent judgment", gradually replacing human independent judgment and thinking based on experience. Over time, laboratory personnel may become increasingly dependent on embodied intelligent agents for tasks such as testing and decision-making, leading to a gradual weakening of their own sense of agency and core competencies, ultimately resulting in a substantive relinquishment of their primary role. As Kant argued in his categorical imperative, humanity must always be treated as an end in itself, never merely as a means — a principle that remains central to contemporary AI ethics discourse [27, 28]. Human development and the realization of the value of life are the ultimate goals of all technology; it is humans who bear responsibility, not robots.

Faced with the above challenges, the introduction of embodied intelligence technology into oil and gas laboratories requires sound top-level design. Designers must be familiar with the underlying logic of laboratory operations, possess an awareness of multidisciplinary integration, and have a forward-looking vision [29]. As oil and gas laboratories enter the era of embodied intelligence technology, a strategy of "phased implementation, pilot-first" should be adopted. Application validation should be prioritized in scenarios such as repetitive testing and high-risk operations, while simultaneously advancing talent cultivation and institutional innovation, gradually building a new ecosystem of smart laboratories characterized by human-machine collaboration and complementary strengths. Recently, local governments have been vigorously promoting the "One-Person Company" (OPC, i.e., a "single person + AI" business entity). The concept of a "One-Person Laboratory" (OPL) may be viewed as a research-oriented extension of the "One-Person Company" model.OPL is precisely the concrete manifestation of the OPC model in the field of scientific research and technological development—a "super researcher" empowered by AI, capable of independently completing the entire process from experimental design to data analysis. It is foreseeable that in the future, a top-tier scientist or engineer with a brilliant idea might indeed be able to rely on a "One-Person Laboratory" and powerful AI to achieve research outcomes comparable to those of large teams.

## 5 Conclusions

The transformation and upgrading of oil and gas field testing laboratories fundamentally requires overcoming reliance on passive testing models and achieving a paradigm shift toward "proactive, intelligence-driven operations". The concepts of "physical presence" and "device-cloud collaboration" embodied by embodied intelligence offer a feasible technical pathway for addressing systemic dilemmas such as heavy repetitive labor and the separation of research and testing functions. However, the deployment of this technology still faces multiple real-world barriers, including high costs, institutional adaptation challenges, and talent structure mismatches. Therefore, future advancement should be approached cautiously. Instead, a prudent strategy of "pilot-first, phased implementation" should be adopted, with initial testing and application carried out in typical scenarios such as repetitive testing and high-risk environments, thereby gradually cultivating a new ecosystem of smart laboratory management characterized by human-machine collaboration through practical experience.

Notably, the "One-Person Laboratory" (OPL) may become a reality in the near future. OPL is not intended to replace traditional research institutions, but rather to establish a new, AI-empowered research paradigm that is more flexible and lower in cost. It is foreseeable that in the not-too-distant future, a top-tier scientist with a brilliant idea may be able to independently complete the entire process from experimental design to knowledge production. This represents not only an improvement in efficiency but also a release of human creativity and agency, enabling technological innovation to truly return to its ultimate value of "serving humanity."

## Data Availability Statement

Not applicable.

## Funding

This work was supported by the CNPC Research and Application-Oriented Scientific and Technological Projects under Grant 2023ZZ16 and Grant 2026ZG060.

## Conflicts of Interest

Qiang Kang, Jiahuan He, Xingwang Tian, Hongyu Yao, Ruilong Tang, and Jie Tan are affiliated with the Exploration and Development Research Institute, Southwest Oil and Gas Field Company, PetroChina,

Chengdu 610213, China. Jiahuan He is additionally affiliated with the State Key Laboratory of Enhanced Oil & Gas Recovery, Beijing 100083, China and the Shale Gas Geological Evaluation and Efficient Development Sichuan Provincial Key Laboratory, Chengdu 610213, China. Hang Yang is affiliated with the Shale Gas Geological Evaluation and Efficient Development Sichuan Provincial Key Laboratory, Chengdu 610213, China and Southwest Oil and Gas Field Company, PetroChina, Chengdu 610051, China. The authors declare that these affiliations had no influence on the study design, data collection, analysis, interpretation, or the decision to publish. Jiahuan He served as an Associate Editor of the *Journal of Geo-Energy and Environment* at the time of manuscript submission. To ensure the integrity of the peer-review process, Jiahuan He was not involved in the editorial handling, peer review, or decision-making process for this manuscript, which was handled independently by another editor. The remaining authors declare no conflicts of interest.

## AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

## Ethical Approval and Consent to Participate

Not applicable.

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