

Technological Innovations and Intelligent Laboratory Development in Refining and Chemical Enterprises: A Systematic Review and Future Directions

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Abstract: Amid the accelerating wave of digital transformation sweeping the global energy sector, laboratories in refining and chemical enterprises are undergoing a paradigm shift—from conventional manual operations toward intelligent, automated management systems. This study systematically investigates the construction pathways and technical architectures underlying intelligent laboratory systems within the petrochemical industry, with particular emphasis on how frontier technologies—including large-scale AI models, robotics, and the Internet of Things—are reshaping operational modalities. By integrating real-time data acquisition, mobile applications, intelligent analytics, and automated instrumentation, the proposed intelligent laboratory framework yields substantial operational improvements: a 40% increase in detection efficiency, 99.8% data accuracy, and an 80% acceleration in decision response time. Through in-depth analysis of benchmark implementations at Tianjin Petrochemical, Guangdong Petrochemical, and Fushun Petrochemical, this paper identifies key technological breakthroughs—namely the cloud-edge-end collaborative architecture, multimodal data fusion, and domain-specific knowledge graphs for quality control. It further addresses organizational challenges encountered during implementation and outlines prospective development trajectories. The findings offer a systematic and replicable reference framework for the intelligent transformation of laboratories in the refining and chemical sector.

Keywords: Refining and chemical enterprises; Intelligent laboratory system; Large AI model; robot; Intelligent decision-making.

1. INTRODUCTION

Inevitable Trend of Intelligent Transformation in Refining and Chemical Laboratories. Against the background of global energy structure adjustment and industrial upgrading, refining and chemical enterprises are facing unprecedented pressure to improve quality and efficiency. As the core unit of enterprise quality control, the operational efficiency of laboratories and the ability to mine data value directly affect product quality and production costs. Traditional refining and chemical laboratories generally have three major pain points: serious data silos, manual recording leading to 20% of test reports requiring rework, resulting in annual quality costs exceeding one million yuan; low process efficiency, with sample circulation cycles as long as 72 hours, severely restricting the response to device operation optimization; high compliance risks, as paper documents are difficult to meet regulatory traceability requirements such as CNAS accreditation. These systemic bottlenecks urgently need to be addressed through laboratory informatization and intelligent upgrading.

The intelligent laboratory system (LIMS) has evolved from a mere data recording tool into a quality decision-making hub, becoming a key fulcrum for the digital transformation of refining and chemical enterprises. Modern intelligent laboratory systems, through the in-depth integration of technologies such as the Internet of Things, big data, and artificial intelligence, have achieved automated testing processes, intelligent data analysis, and closed-loop quality control. The practice of Fushun Petrochemical Company shows that after the launch of the intelligent LIMS system, the communication efficiency of various specialties has increased by 70%, the sample circulation efficiency has improved by 30%, the risk early warning response time has risen by 80%, and data consistency has reached 99.8%. These improvements have significantly enhanced the enterprise's quality control level and market competitiveness.

Breakthroughs in large AI models and robotics have injected new momentum into laboratory intelligence. The petroleum molecular information database and molecular gene model developed by the team of Academician Xu Chunming of the Chinese Academy of Sciences have achieved high-precision characterization of crude oil and its fractions, converting petroleum molecular-level information into a language recognizable by computers, laying the

foundation for subsequent model construction. The first domestic petrochemical large model deployed in Ningbo, through training and analysis of massive real-time data, can simulate the crude oil processing process in real time, compressing the originally required 5 ~ 6 hours of oil product switching operations to 4 hours, greatly improving production efficiency. At the same time, robotics technology has also been widely applied in laboratory scenarios, from quadruped robot VOCs detection to robotic arm automatic sampling, with intelligent equipment replacing manual labor in dangerous and repetitive tasks.

This paper aims to systematically explore the construction methods of intelligent laboratory systems in refining and chemical enterprises, focusing on analyzing key technological breakthroughs and application practices, so as to provide replicable solutions for the digital transformation of the industry. The research will focus on three core issues: How can intelligent laboratory systems improve operational efficiency through technological innovation? How to ensure data accuracy and intelligent decision-making? What challenges are faced during implementation and what are the corresponding strategies?

2. SYSTEM ARCHITECTURE AND KEY TECHNOLOGIES

The construction of an intelligent laboratory system requires the dual drive of top-level design and technological innovation. The complexity and high standards of the refining and chemical industry require the system architecture to have elastic scalability, safety, reliability, and intelligent decision-making capabilities. Modern intelligent laboratory systems have developed a multi-level, multi-module collaborative system, achieving a comprehensive innovation in laboratory operations by integrating cutting-edge information technology and automated equipment.

2.1 Cloud-Edge-End Collaborative Architecture

The intelligent laboratory system adopts a layered and decoupled design concept, constructing a three-level collaborative architecture of "cloud decision-making - edge computing - terminal execution". In the smart laboratory project of Fushun Petrochemical, a quality data center is deployed in the cloud, integrating more than 60 master data models and over 200 business data models to achieve global sharing and value mining of detection data. The edge layer consists of a distributed microservice cluster, supporting elastic deployment of algorithms such as SPC statistical process control and multivariate analysis.

Automatic data collection is a basic function of intelligent laboratories. The instrument data collection system independently developed by Kunlun Digital Intelligence, through the deployment of this module on the laboratory instrument workstation, utilizes three synchronization technologies provided by the module: wired transmission, wireless scanning, and offline import, significantly reducing the cost of enterprise instrument integration and supporting transformation. At the same time, the system automatically acquires and parses instrument test results, and the processed data is automatically uploaded to the system database. These related functions have comprehensively improved the accuracy and traceability of experimental data, realized automated management of data collection, reduced manual entry workload, achieved the goal of efficient management, and increased the automatic collection rate of laboratory instruments to over 95%.

2.2 Modular Function Design

The intelligent laboratory system follows the principle of "high cohesion - low coupling" and decomposes core functions into standardized service modules. The sample full life cycle management module realizes the whole-process tracking from sampling to disposal through RFID and two-dimensional code technology; the application case in Tianjin Petrochemical shows that the sample circulation efficiency is increased by 9 times. The real-time quality monitoring module integrates the MSPC (Multivariate Statistical Process Control) algorithm, which can identify process parameter deviations of the 0.01% magnitude. The intelligent closed-loop control module dynamically adjusts PID parameters based on reinforcement learning, improving the sulfur content control accuracy of the hydrogenation unit by 80%. The compliance engine module has built-in more than 200 SOP electronic processes and automatically generates audit trail records that meet the requirements of FDA 21 CFR Part 11.

The popularization of mobile applications has greatly improved the flexibility of laboratory work. The mobile APP developed by the system supports functions such as real-time query of sample status, instant push of abnormal results, and electronic signature approval, freeing technical personnel from the constraints of fixed workstations.

2.3 Cross-System Integration and Data Governance

Addressing the heterogeneous data integration issue between intelligent laboratory systems and production systems such as MES and ERP is a core challenge in architectural design. At the data governance level, the system implements a "three-step" strategy: At the collection end, multi-protocol adaptation technology is used to support industrial protocols like Modbus and Profinet, increasing the data collection coverage rate of old equipment from 60% to 98%; The transmission layer adopts a "data lake + stream computing" architecture, with batch processing data stored in the Hadoop distributed system, achieving a daily processing capacity of 15TB; The application layer implements data verification based on the ISO 8000 standard, resulting in an abnormal data identification accuracy rate of 99.7%. This end-to-end data governance system has laid a solid foundation for closed-loop quality control.

3. BREAKTHROUGHS AND APPLICATIONS OF INTELLIGENT TECHNOLOGIES

The core competitiveness of intelligent laboratory systems lies in the in-depth integration of advanced algorithms and intelligent equipment. With the rapid development of large AI models and robotics technology, refining and chemical laboratories are undergoing a qualitative leap from automation to intelligence. These innovative technologies not only improve laboratory operational efficiency but, more importantly, change the decision-making model of quality management, enabling predictive maintenance and forward-looking decision-making.

3.1 Laboratory Applications of Large AI Models

The launch of large petrochemical models marks a new stage in industrial intelligence. The first domestic large petrochemical model, collaboratively developed by SUPCON Technology with enterprises such as Zhenhai Refining & Chemical and Ningbo Wanhua, can real-time simulate crude oil processing processes and predictively optimize production process parameters through the training and analysis of massive real-time data. In crude oil processing scenarios, the model simplifies the oil product switching operation, which originally relied on 老师傅's experience and took 5-6 hours, into a standardized process guided by the model for operators, reducing the time to 4 hours. Molecular-level modeling technology provides a new tool for product quality control. The knowledge graph also supports semantic search functions; for example, querying "countermeasures for high sulfur content" returns solutions such as adjusting hydrogenation reaction temperature and adding sulfur injection agents, sorted by implementation cost.

3.2 Integrated Innovation of Robotics Technology

Quadruped robots have broken through the spatial limitations of traditional detection. The quadruped robot developed by the Digital Intelligence Research Institute has successfully completed VOCs detection and patrol tests at Jinzhou Petrochemical and Jinxi Petrochemical, demonstrating excellent adaptability in complex environments. With the intelligent path planning and image recognition technology of the Kunlun large model, the robot can independently climb continuous multi-layer industrial steps, cross low pipeline obstacles, and pass through narrow channels, solving the safety risks of manual detection in high-risk environments. The research team also built an indoor simulation training laboratory to simulate real refining and chemical scenarios for technical verification, significantly reducing training costs.

The robotic arm automatic sampling system has revolutionized laboratory operations. The "fully automatic contactless liquid sampling platform" deployed by Zhenhai Refining & Chemical can automatically complete QR code identification, lid opening, pipetting, transfer, labeling, and recovery of samples, achieving zero contact with samples during operation with an accuracy rate of 100%. The intelligent unmanned sample collection and delivery system composed of AGV unmanned sample delivery vehicles and automatic sample cabinets applied by Tianjin Petrochemical has realized full unmanned sample circulation, reducing sample delivery time by 70%.

4. SYSTEM APPLICATION EFFECTS AND CASE ANALYSIS

The value of intelligent laboratory systems is ultimately reflected in the business benefits created in practical applications. By analyzing industry benchmark cases, we can clearly see how technological innovation is

transformed into quality optimization, efficiency improvement, and cost savings. These cases not only verify the feasibility of intelligent laboratory systems but also provide replicable experience templates for industry promotion.

4.1 Full-Process Quality Control System

The Kunlun MES domestic R&D project of Fushun Petrochemical has built a closed-loop quality chain from crude oil evaluation to finished product delivery. The system enables automatic generation of unit processing plans from crude oil evaluation data, and real-time feedback of distillation outlet quality data to the LIMS system for compliance checks. After the project was put into operation, data barriers between modules were completely broken down, and electronic original records meeting international standards were automatically generated, with an estimated annual savings of 10 tons in paper consumption alone. More importantly, the system has increased the communication efficiency of various professions by 70%, improved sample circulation efficiency by 30%, compressed upload time to less than 1 minute, increased risk warning response time by 80%, and achieved data consistency of 99.8%.

The benchmark smart laboratory project jointly built by Tianjin Petrochemical and SUPCON Technology has achieved a qualitative leap through full-process automation. The project includes an intelligent unmanned analysis system for the full water quality process, an intelligent unmanned analysis system for the full chromatographic liquid sample process, and an intelligent equipment network such as the plant-wide intelligent unmanned sample collection and delivery system. The smart laboratory uses the LIMS system to efficiently assign tasks; laboratory technicians only need to place the samples, and the system automatically completes scheduling, assignment, and analysis, with experimental results uploaded in real time.

4.2 Dual Optimization of Efficiency and Cost

Intelligent laboratory systems demonstrate significant advantages in testing efficiency. In traditional laboratory testing processes, manual recording, sample transfer, and report preparation account for 30% ~ 40% of working hours. Through process reengineering and automation transformation, Guangdong Petrochemical has shortened the testing cycle from 3 days to 8 hours, helping to increase the response speed of unit adjustments by 60%. The plant-wide intelligent unmanned sampling and delivery system in the Tianjin Petrochemical project uses automatic sample cabinets and unmanned vehicles to achieve unmanned sample circulation, reducing manual intervention by more than 90%.

Cost control is another core value of intelligent laboratory systems. In traditional laboratories, labor costs account for approximately 60% of operating expenses, while intelligent systems can reduce overall costs by 15% to 20% through optimized resource allocation and waste reduction. Fushun Petrochemical replaced 50% of paper documents with electronic records, saving 500,000 yuan in consumables costs annually.

4.3 Comprehensive Improvement of Safety and Compliance

Intelligent laboratory systems have significantly improved safety management through real-time monitoring and early warning mechanisms. The Tianjin Petrochemical Smart Laboratory reduces accident risks through real-time monitoring and early warning of experimental processes, and accurately identifies and improves process bottlenecks by combining AI and big data analysis.

In terms of compliance management, intelligent systems provide unprecedented solutions. The complete data traceability chain built in the Fushun Petrochemical project meets international standards such as ISO 17025. The innovatively developed twelve major module functions, including automatic data collection, electronic quality inspection forms, analysis process control, and abnormal data judgment, reduce compliance audit time by 60%. The intelligent system also has built-in over 200 electronic SOP processes and automatically generates audit trail records that meet FDA 21 CFR Part 11 requirements, bringing the laboratory quality management system to an internationally advanced level.

5. IMPLEMENTATION CHALLENGES AND FUTURE OUTLOOK

The construction of intelligent laboratory systems has not been smooth sailing, and there are still multiple challenges in technology integration, organizational change, and talent development. In particular, the refining and

chemical industry has strong data sensitivity, scarce reliable data sources, serious enterprise data silos, and some historical data has problems of repetition and authenticity.

The issue of model credibility has hindered the widespread application of AI technology. The black-box nature of AI models leads to insufficient trust from enterprises, especially in critical decisions involving production safety, where engineers tend to rely on experience rather than algorithmic recommendations. At the same time, resistance to organizational change cannot be ignored. During a pilot project at a refinery, the quality department was worried that automation would weaken its voice, and the production department resisted external system intervention in operational authority.

5.1 Future Technology Development Directions

The application of large models in the refining and chemical industry will feature multimodal understanding capabilities, capable of processing various types of information such as text, images, and spectral data, supporting more complex decision-making scenarios. The in-depth application of robotics technology can already enable free movement in laboratories, automatic reagent addition, and independent data analysis. Over the next five years, we expect to see more autonomous experimental systems deployed in refining and chemical laboratories, enabling 7 × 24 hours of uninterrupted operation, freeing scientists from repetitive tasks to focus on creative research. The collaborative work of quadruped robots, drones, and robotic arms will form a complete laboratory automation ecosystem.

5.2 Industry Ecosystem and Talent Development

Intelligent laboratory systems require interdisciplinary talents who understand both refining and chemical processes, as well as data science and AI technologies. At the enterprise level, a hierarchical training system should be established, with differentiated courses designed for managers, technical experts, and operators. Industry associations should take the lead in formulating intelligent laboratory construction guidelines, covering key aspects such as architectural design, data interfaces, and safety specifications.

6. CONCLUSION

The construction of intelligent laboratory systems is a key path for the digital transformation of the refining and chemical industry, and its significance goes far beyond technology itself, representing an innovation in quality management concepts. With continuous technological breakthroughs and the improvement of the industry ecosystem, intelligent laboratories will evolve from single-point applications to full-process collaboration, from auxiliary decision-making to autonomous optimization, and ultimately realize the vision of "quality as a service," providing solid support for the high-quality development of refining and chemical enterprises.

Fund Project

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