Volume 9, Issue 11, November – 2024 International Journal of Innovative Science and Research Technology
ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24NOV818

AI Applications and Emerging Trends in Petroleum Exploration and Development

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Abstract:- This paper examines how AI is transforming petroleum exploration and development, addressing current applications and future directions. Machine learning is being used to enhance tasks like identifying rock types, reconstructing logging curves, and estimating reservoir parameters, showing promise in improving data processing and interpretation. In seismic analysis, computer vision helps with identifying initial seismic signals and detecting faults. Deep learning and optimization techniques are applied in reservoir engineering, enabling real-time waterflooding optimization and production forecasting for oil and gas. Data mining is also enhancing drilling, completion, and facility operations, leading to smarter equipment and integrated software.

Looking ahead, AI in petroleum is poised to advance with intelligent production tools, automated data processing, and specialized software platforms. Future innovations are expected in digital basin modeling, fast imaging logging tools, advanced seismic systems, smart drilling and fracturing technologies, and real-time monitoring of injection and production zones.

I. INTRODUCTION

Artificial Intelligence (AI), introduced in 1956 at the Dartmouth Conference by John McCarthy and his team, aimed to use machines to replicate human cognitive abilities. While interpretations of AI vary, it essentially involves creating machine-based versions of human-like thought processes. This study investigates AI's evolving role in oil exploration and development, responding to key industry demands. We review AI applications in areas like logging, geophysical exploration, drilling and completion (D&C), reservoir engineering, and surface facility management, highlighting current progress and future potential.

Key AI technologies include machine learning, data mining, natural language processing, pattern recognition, computer vision, and knowledge graphs. With the explosion of big data, deep learning, and advancements in computing power, AI has rapidly progressed, revolutionizing fields like healthcare, transportation, agriculture, and the internet. As a core driver of the Fourth Industrial Revolution, AI is helping transition society into an era of intelligence.

Today, as domestic oil reserves decline in quality and mature fields approach late-stage production with high water cuts, sustaining economic stability and energy security requires renewed focus on innovative exploration and development. With global trends in digitalization, information technology, and automation, intelligent exploration and development is gaining recognition as the industry’s future. This approach promises enhanced efficiency, improved quality in exploration and development, reduced costs and risks, and greater capacity to tackle complex reservoirs. This paper delves into these advancements and the transformative potential of AI within petroleum exploration and development.

II. R&D OF ARTIFICIAL INTELLIGENCE IN OILCOMPANIES

Oil companies are increasingly embracing strategies like open innovation, partnerships with educational institutions, and collaborations with IT companies to advance the oil and gas industry’s intelligence. Strategic alliances with tech giants are helping companies achieve smarter, data-driven operations. Partnerships like Total with Google Cloud, Chevron with Microsoft, and Shell with HP are leading to innovative solutions in upstream operations. Shell’s “Smart Field” initiative, for instance, focuses on intelligent wells, real-time production optimization, and collaborative working environments, while Chevron’s “i-Field” centers on drilling and production efficiency. BP’s “Field of the Future” uses real-time data to optimize operational processes, and GASPROM’s digital transformation focuses on several key areas, including digital exploration, safety systems, and efficient large-scale project management.

BP Ventures has invested $20 million in AI software with Beyond Limits to streamline reservoir location, crude oil refinement, and sales, while an additional $5 million investment in Belmont Technology supports BP’s digital transition. Total and Google are jointly developing AI-driven methods to enhance seismic data interpretation and improve exploration efficiency.

Collaborations like Shell and Microsoft's Geodesic platform are refining well trajectory control to improve accuracy in resource extraction, providing real-time decision-making capabilities. ExxonMobil and Microsoft are developing a secure cloud platform for real-time data collection across expansive fields, helping optimize drilling and resource management. Chevron, Schlumberger, and Microsoft are similarly collaborating to advance intelligent solutions in the industry. These partnerships and innovations mark a shift toward a more efficient, intelligent oil and gas sector.

Table 1. Global Overview of AI Strategies Among Leading Oil and Gas Companies and Service Providers

No.	Company	Strategic Focus	AI Platform	Partners
1	BP	Decision automation for upstream/downstream; well control	Sandy	Beyond Limits, Belmont Technology
2	Shell	Drilling data processing algorithms	Geodesic	Microsoft
3	ExxonMobil	Data integration, real-time E&P solutions	XTO	Microsoft
4	Total	Intelligent seismic imaging	Cloud Platform	Google, Microsoft
5	Chevron	E&P, storage, and transportation projects	DELFI	Schlumberger
6	Schlumberger	E&P, storage, and transportation projects	DELFI	Microsoft, Chevron
7	Baker Hughes	Seismic modeling, malfunction prediction, supply chain optimization	Desktop Platform, Azure	NVIDIA, Microsoft
8	Halliburton	Reservoir characterization and simulation intelligent basins, intelligent logging, intelligent geophysical	Azure	Microsoft
9	PetroChina	exploration intelligent drilling & completion, intelligent oil production, intelligent, fracturing, and intelligent equipment	Cognitive computing platform	Huawei
10	Sinopec	Intelligent basins, logging, geophysics, drilling & completion, fracturing, equipment	Dream Cloud Platform, Cognitive Computing Platform, Oilfield Smart Cloud Industrial Internet Platform	Huawei, Ali
11	CNOOC	Intelligent oilfields, E&D data management	Technology Platform	Ali

This comparison highlights the strategic AI applications and industry partnerships of major oil and gas companies, underscoring a shared commitment to digital transformation, decision automation, and advanced E&P capabilities.

Schlumberger's DELFI cloud platform consolidates data from multiple sources to create a shared ecosystem and speed up analysis. Halliburton and Microsoft have joined forces to use Azure Intelligent Cloud in exploration and development, integrating deep learning for reservoir characterization and simulation to enable digital operations.

Baker Hughes, in partnership with NVIDIA, employs AI and GPU-accelerated computing for real-time data extraction, improving seismic modeling, machinery malfunction prediction, supply chain management, and cost efficiency across the oil production lifecycle. In November 2019, Baker Hughes, C3.ai, and Microsoft collaborated to deliver enterprise AI solutions on Microsoft's cloud for the energy sector.

Logging has advanced from analog to intelligent systems, driven by the need for better data collection techniques. Complex reservoirs and varied logging environments require new approaches in downhole data acquisition and AI-powered tools for accurate geological sensing. Companies like Schlumberger offer solutions such as the Remote Logging Center, Intelligent Formation Tester, and Techno, a software for data processing, supported by a global infrastructure of servers and experts.

China National Petroleum Corporation (CNPC) has launched its Cognitive Computing Platform (E8) with pilot projects across major oilfields, alongside the Dream Cloud Platform, built on a unified data lake and technology infrastructure to support AI integration. Since 2012, China Petrochemical Corporation (Sinopec) has pioneered intelligent manufacturing, establishing smart factories, oilfields, and research institutes, supported by the Oilfield Smart Cloud Industrial Internet Platform to link IT with core business functions. In March 2020, China National Offshore Oil Corporation (CNOOC) introduced its "Top-Level Design Scheme for Digital Transformation," setting a detailed plan to develop intelligent oilfields and achieve comprehensive data governance in exploration and development.

III. APPLICATION OF ARTIFICIAL INTELLIGENCE IN PETROLEUM EXPLORATION AND DEVELOPMENT

A. Logging

Logging technology, which originated in 1927, has progressed significantly over the past 90 years, moving from analog to digital, then direct digital and imaging logging, and now advancing into the era of intelligent logging.

➢ *Logging Data Collection*

The complex nature of reservoirs, diverse exploration targets, and challenging logging environments highlight the need for innovative data collection methods, particularly for downhole parameter acquisition and data transmission. Integrating AI into these processes enhances accuracy, efficiency, and safety in geological sensing. Industry leaders have developed commercialized data acquisition and remote logging tools—such as Schlumberger's Remote Logging Center, Intelligent Formation Tester, and the Tocology wellbore software—featuring intelligent data processing and interpretation capabilities. Schlumberger's global infrastructure includes 11 data server centers and 14 remote logging centers, supported by a team of 108 engineers, enabling remote collaboration and decision-making for over 10,000 logging operations annually. In China, petroleum companies and research institutions are exploring networked surface facilities, intelligent winches, and remote logging technology, with early-stage applications and research on intelligent downhole robotics also underway.

➢ *Logging Data Processing and Interpretation*

Due to the vast and heterogeneous nature of logging data, interpretation is often complex, making it challenging to accurately identify productive zones. AI has become critical in improving interpretation efficiency and accuracy, with applications like automatic depth correction, automated report generation, intelligent stratification, curve reconstruction, lithology identification, imaging interpretation, reservoir parameter estimation, oil and gas potential evaluation, shear wave velocity prediction, and fracture analysis. Intelligent curve reconstruction leverages deep learning, correlation analysis, and other algorithms to detect and repair errors, gaps, and missing portions in logging data by analyzing relationships between various logging curves. Methods such as neural networks, ensemble learning, and clustering algorithms are applied to enhance this process. Zhang et al. [2] have proposed a method for Recurrent neural networks (RNNs), specifically LSTM networks, are now used to reconstruct logging curves, offering improved accuracy over traditional methods when tested against real logging data.

Lithology identification follows two main approaches. The first involves core sampling and analysis, where advancements in scanning technologies have generated a large collection of core images, including thin sections, CT, and SEM images, used in exploration. Software like Avizo and PerGeos now supports automatic lithology identification, but these tools still require significant human-computer interaction and expertise. Most thin-section analysis is still done manually, and applying deep learning to core image analysis is in early stages.

The second approach uses logging curves for lithology identification. Professionals interpret data to train AI-based models for this purpose. For example, Jiang et al. [3] used algorithms like Boosting Tree, Decision Tree, and Support Vector Machine on expert-annotated logging data, achieving over 80% prediction accuracy when compared with mud-logging benchmarks.

Imaging logging has advanced to convert raw logging curves into visual images representing geological features. With the integration of deep learning, researchers are now combining image processing to enable automated interpretations. Ren et al. [4] applied U-Net image segmentation for automated boundary recognition in electrical imaging logs, using machine learning to classify geological features. However, progress is limited due to scarce labeled data in this field.

In reservoir parameter estimation, AI applications began with traditional machine learning algorithms like Support Vector Machine and linear regression to predict porosity, permeability, and saturation. With AI advancements, more complex neural networks, including BP, LSTM, Random Forest, and Gradient Boosting Decision Tree (GBDT), are now used for these estimations.

➢ *Integrated Software*

Globally, Schlumberger has developed a collaborative digital workflow using tools like Petrel, Techlog, and Eclipse to mitigate uncertainty in exploration. Their DELFI platform provides an intelligent suite for data standardization, cleaning, interpretation, and submission. The Techlog wellbore software also supports intelligent curve analysis, prediction, and reconstruction, enhancing interpretive accuracy.

In China, platforms such as CNPC's Dream Cloud Collaboration Platform, LEAD for logging processing, and CIFlog for multi-well formation evaluation have been implemented. AI applications in reservoir characterization, simulation, and multi-well logging interpretation have shown promising preliminary results, with a geo-steering system for horizontal drilling also under development.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24NOV818

B. Geophysical Prospecting

Research in "AI + Geophysical Exploration" is expanding rapidly, integrating high-performance computing, 3D visualization, and networked technologies in geophysical prospecting, which was one of the first fields to adopt digital processes.

➢ *Geophysical Prospecting Equipment*

AI in geophysical equipment is focused on intelligent vibroseis, UAVs, and seismic instrumentation. Intelligent vibroseis systems can adjust output, frequency, scan time, and phase based on specific surface and subsurface conditions, enhancing both safety and environmental compliance. Intelligent UAVs provide high-precision terrain mapping, risk assessment, node monitoring, data recovery, material transport, and rescue capabilities for geophysical operations.

➢ *Seismic Instrumentation*

New advancements in seismic instrumentation, such as the G3i (wired), Hawk (node), and eSeis (node) systems, have modernized the field. Ocean bottom node (OBN) technology development has also solved limitations related to obstacle-crossing, observation azimuth, offshore noise, and single-component reception. **Geophysical Acquisition** The integration of cloud computing, AI, robotics, and communication technologies has evolved geophysical acquisition from digital to intelligent processes. These improvements include non-inductive digitization, closed-loop automation, equipment "robotization," and predictive production modeling. Digital seismic crews, now leveraging IoT and cloud computing, facilitate wireless and real-time digital management of field operations, personnel, and HSE standards, further optimizing workflows with remote support capabilities.

➢ *Seismic Data Processing and Interpretation*

AI has enhanced seismic data processing and interpretation in structural analysis (fault and horizon detection), noise reduction, facies identification, and more. Techniques like target detection and segmentation, which are essential to computer vision, improve both processing speed and accuracy.

- Fault Recognition: Deep learning, especially convolutional neural networks (CNNs), has made fault recognition more precise. Wu et al. [5] developed an encoding-decoding CNN that excels at fault detection and slope estimation using synthetic 3D seismic images, outperforming traditional methods.
- Seismic Facies Recognition: Deep learning models, including CNNs, RNNs, and GANs, are increasingly used to classify seismic waveforms directly, surpassing traditional attribute clustering methods. Zhang et al. [6] used the DeepLabv3+ codec, which effectively captures multi-scale semantic details, offering superior accuracy for seismic facies.
- Seismic Inversion: Seismic inversion, which correlates seismic and logging data, has seen progress with AI. Phan et al. [7] employed a CNN-based cascade method, creating a deep learning model that performs pre-stack seismic inversion, predicting impedance by learning rock property relationships from seismic amplitude.
- First Break Picking: To speed up this crucial yet time-consuming step, Ma et al. [8] developed an automatic first break extraction method, improving efficiency in seismic processing.
- Event Picking with Improved 2D Pixel Convolution Networks

An advanced 2D pixel convolution network has redefined event picking by treating it as a binary image segmentation task. Here, signals before and after the first break are labeled as 1 and 0, respectively. Real borehole seismic data analysis has validated this method, demonstrating its clear advantages over traditional automatic picking techniques.

C. Drilling and Completion (D&C)

D&C technology has evolved from conceptual ideas to an automated, intelligence-driven phase, guided by foundational principles, tools, and specialized equipment. This field is now focused on integrating intelligent automation, transforming drilling operations to increase precision and productivity.

➢ *Intelligent Drilling and Completion (D&C)*

Intelligent D&C represents the next stage in drilling, where intelligent software connects surface equipment and downhole tools in a closed-loop system powered by models and smart decision-making. Key tools include sensor-embedded drill pipes, intelligent drill bits, and rotary steering systems, all coordinated with surface equipment such as rig floor robots and automated tripping and bit-feeding systems. This software-led integration enables precise, automated drilling aligned with geological data, enhancing resource extraction. While in China, intelligent D&C is in early stages with a single-technology R&D focus, there is significant potential for growth compared to established international advancements.

➢ *Key Technologies in Intelligent D&C*

Core intelligent D&C technologies include well trajectory optimization, intelligent steering, and rate of penetration (ROP) optimization. Using AI algorithms like genetic algorithms and neural networks, well trajectory optimization fine-tunes parameters like hole azimuth. Intelligent steering incorporates real-time AI monitoring, seismic-while-drilling, and near-bit measurements for predictive control, while ROP optimization leverages algorithms like random forest and particle swarm for dynamic parameter matching between formation, bit, and drilling parameters.

➢ *Intelligent Drilling and Completion Equipment*

Internationally, advanced surface equipment includes rig floor robots, automatic tripping and bit-feeding mechanisms, automated pressure control, and real-time drilling fluid monitoring. Downhole, intelligent drill bits and pipes facilitate unmanned, precise drilling, reducing risk and cost. The commercialized rotary steering system allows simultaneous measurement and control for enhanced steering and drilling. Neural network-driven parameter optimization models maximize resource extraction by dynamically aligning real-time and ideal trajectory data.

In China, although automated drilling rigs with tubular control are in use, challenges persist in sensor reliability, diagnostic accuracy, and hydraulic control precision. Automated pressure management is common, yet further advancements are needed in real-time hole condition analysis and formation recognition. Domestically made MWD tools are promising but require improvements in geo-steering and intelligent navigation capabilities.

➢ *Intelligent D&C Software*

Key software solutions, including digital twins, automated control systems, drilling simulations, and remote decision-making tools, are now commercially available, driving intelligent advancements in the D&C field.

- *Continuous Advancements in Intelligent D&C Software*

International companies are transforming drilling and completion (D&C) processes by incorporating machine learning, big data, and cloud computing to predict borehole environments and understand formation mechanics. Key developments include big data integration platforms, cloud-based design and optimization systems, and software for fracturing optimization. Together, these innovations improve D&C accuracy, forecast precision, and control, pushing D&C operations toward full automation, efficiency, and intelligence.

- *Halliburton's Well Construction Project 4.0*

leverages big data and optimization platforms to create a Digital Twin Wellbore, allowing for pre-drilling simulation, real-time decision-making, and post-drilling analysis. Schlumberger's DELFI platform with DrillPlan significantly reduces drilling design timelines, while ConocoPhillips' IDW platform enhances data processing, optimizes completion, and improves formation analysis. China's intelligent D&C software is still in early development, offering essential functions like D&C design and monitoring, though improvements are needed in data standards, model integration, and accuracy for practical field application.

- *Intelligent D&C Integration Platforms*

Schlumberger's "Drilling System of the Future" integrates digital technology, equipment, and software with over 1,000 sensors and an automated drill pipe handler, allowing for automated monitoring and control of 350 drilling tasks. National Oilwell's platform, evolve, combines NOVOS (surface control software), Intelliserv (intelligent drill pipe), BlackSteam (MWD tool), and DrillShark (optimization software) into a closed-loop system that synchronizes downhole and surface data for drilling simulations. Applied in the Eagle Ford shale, it achieved a 37% reduction in net drilling time, though further refinement is needed in system cost and reliability.

D. Reservoir Engineering in the Industry 4.0 Era

Reservoir engineering focuses on understanding the migration and displacement of oil, gas, and water within porous media to improve recovery rates. The transition to intelligent reservoir engineering incorporates algorithms and software for comprehensive reservoir modeling, enabling dynamic management and predictive capabilities.

➢ *Reservoir Performance Analysis and Simulation*

Artificial intelligence is increasingly applied in reservoir engineering to manage real-time waterflooding, predict production, estimate saturation, and select production measures. In waterflooding, data mining and optimization algorithms adjust production parameters. Jia et al. applied traditional simulation and optimization methods to analyze flow patterns in zonal injections and quantify liquid production by zone, enhancing the assessment of water injection effectiveness. They further developed a machine learning-based approach for fine-tuned injection schemes, establishing an integrated reservoir and production engineering technology that supports intelligent scheme design, optimization, and real-time control.

- *Enhanced Flow Field Identification and Reservoir Analysis with AI*

Jia et al. introduced an AI-based approach to streamline simulation for flow field identification in water-flooded reservoirs. By differentiating streamlines between specific injector-producer pairs, they established a method for optimizing injection, well pattern adjustments, and profile control. Benchmark tests demonstrated high predictive accuracy, supporting decision-making in reservoir management.

- *Production Forecasting*

Researchers apply recurrent neural networks (RNNs) to forecast cumulative oil and liquid production based on reservoir and production parameters. Wang et al. created a long-short-term memory (LSTM) network model to predict production in ultra-high water cut periods, surpassing traditional waterflooding charts and fully connected neural networks (FCNN) in accuracy. Kubota et al. employed machine learning, specifically linear regression and RNN, to predict oil production for mature fields developed through water or steam injection, relying only on production and injection histories. Bao et al. developed an RNN-based workflow linking control parameters like flow rate and

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24NOV818

bottom-hole pressure directly to expected productivity, offering improved reservoir management.

- *Saturation Forecasting and Reservoir Simulation*

To predict water saturation, Tariq et al. optimized Functional Network models with differential evolution, particle swarm optimization (PSO), and CMAES, achieving a 97% accuracy rate using petrophysical data. Shahkarami et al. developed an intelligent model incorporating history matching, sensitivity analysis, and uncertainty evaluation for reservoir simulations, validated by field case studies to accurately predict output, pressure, and saturation while accelerating computations.

- *Optimization of Production Measures*

Artun et al. used a fuzzy reasoning system to convert parameters into fuzzy variables, enabling AI-driven decisions for selecting candidate wells for repeated fracturing in tight sandstone gas reservoirs. Sengel et al. addressed uncertainties in complex carbonate reservoirs by developing an AI method that improves reservoir description, dynamic model calibration, and history matching.

- *Automated History Matching and Numerical Simulation*

For numerical simulations, intelligent models focus on automating history matching to increase simulation speed. Zhang et al. integrated neural simulation protocols with expert systems, enabling the model to update based on simulation-generated data. Costa et al. utilized neural networks and genetic algorithms for field history matching, allowing the system to replicate high-fidelity models and predict field production.

➢ *Integrated Analysis Software*

Globally, tools like Schlumberger’s Eclipse and INTERSECT, Landmark’s VIP, and RFD’s Navigator use AI for automated history matching, boosting simulation efficiency. In China, PetroChina’s HiSim software incorporates deep learning to enhance simulation speed, while IRes, a reservoir analysis tool, uses computational geometry and optimization for real-time monitoring and zonal injection control.

➢ *Summary of Surface Facility Engineering in Oil and Gas Development*

In the oil and gas sector, an oil and gas lease is akin to a "fenceless factory," where creating a digital twin of field surface facilities is essential for intelligent operations. This digital twin, designed with 3D technology and digital delivery, integrates real-time production data and intelligent applications, enabling virtual monitoring, prediction, optimization, and decision-making to continually enhance the performance of real-world facilities.

E. Key Technologies in Surface Facility Engineering

Surface facility engineering has evolved from manual to automated, then to digital, and now integrates AI for fully intelligent fields capable of perception, analysis, prediction, optimization, decision-making, and execution. The core technologies in this area are digital delivery, digital metrology, flow assurance, and pipeline network optimization, as well as enhancements for gathering and storage operations.

➢ *Digital Delivery and 3D Design:*

Digital delivery through 3D design allows cross-functional collaboration, real-time reviews, and synchronized optimization, improving construction efficiency and quality. Despite progress, production data integration, asset co-generation, and data-driven value extraction still need refinement.

- *Digital Metrology:*

Digital and automated metering improves measurement accuracy and efficiency at metering stations. Digital single-well metering uses simulation and reinforcement learning, while indicator diagrams serve as lower-cost alternatives in some setups, though scenarios like low production or heavy oil challenge these technologies' adaptability.

- *Gathering Networks and Flow Assurance:*

Complex gathering networks require safe and stable operations. International software aids with flow assurance and corrosion monitoring, whereas domestic tools mainly simulate flow but lack advanced flow assurance capabilities.

- *Gathering and Storage Stations:*

Optimizing station operations reduces energy consumption and boosts safety. Overseas tools provide basic energy monitoring, parameter optimization, and operational diagnostics, though domestic solutions for large-scale station simulation are limited.

➢ *Intelligent Equipment for Surface Facilities*

Internationally, unmanned aerial vehicles (UAVs) and robots conduct inspections of pipelines and facility stations. Equipped with image recognition and big data analysis, these systems detect risks and offer early warnings with up to 95% accuracy, reducing manual labor and enhancing working conditions. In China, these technologies are in early stages

➢ *Intelligent Software for Surface Facilities*

Commercial software now supports real-time simulations and process twins for production systems, capturing dynamic data to predict scenarios, identify anomalies, and optimize performance. This digital twin capability allows for advanced operation simulations and adjustments, contributing to safer and more efficient oil and gas field management.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24NOV818

➢ *Overview of Surface Facility Engineering Software in Oil and Gas*

- Schlumberger's PIPESIM: A leading steady-state simulator, PIPESIM supports diverse development stages, from early casing and artificial lift design to wellbore optimization. It's applicable across conventional, unconventional gas, and heavy oil reservoirs, making it ideal for managing offshore satellite fields and extensive onshore networks.

- NSI's StimPlan: A comprehensive 3D hydraulic fracturing design tool, StimPlan covers fracturing, acid-fracturing, and packing, supporting both conventional and unconventional reservoirs across vertical, directional, and horizontal wells. Its detailed modeling optimizes well performance, cuts costs, and minimizes environmental impact. Other software like FracproPT, Terrfrac, and GOHFER provide additional solutions for single-well fracturing design and analysis.

- PetroChina's PetroPE: Developed by RIPED, this web-based tool supports diagnostics, optimization, and decision-making for various wells and lift systems. With integrated reservoir productivity, rod/tubing stress, and pump movement analysis, PetroPE achieved a 93% diagnostic accuracy across 30,000 wells, improving efficiency and field management.

Despite these advancements, Chinese surface facility engineering software trails behind international standards, indicating a need for further development and commercialization to close this intelligence gap.

IV. SUMMARY AND PROSPECTS FOR DIGITAL TRANSFORMATION IN OIL AND GAS

Digital transformation in oil and gas leverages IoT, cloud computing, big data, AI, and blockchain to automate data capture, secure storage, and real-time monitoring with intelligent analysis. AI is pivotal in overcoming exploration and development bottlenecks, shifting management from isolated processes to collaborative systems. Key benefits include enhanced quality, cost efficiency, and productivity through:

- Automated Data Collection: Real-time dynamic data enables informed decisions.
- Intelligent Data Processing: Increases interpretation efficiency, reduces expert dependency, optimizes resources, and cuts labor costs.
- UAVs and Electronic Inspections: Minimizes manual labor, promoting employee satisfaction.
- Proactive Fault Detection: Allows preventive measures, improving response times and reducing maintenance costs.
- Dynamic Operations Management: Enhances emergency responses and reduces production losses.

➢ *Challenges in Applying AI in Oil Exploration and Development (E&D)*

Applying AI in oil and gas exploration and development (E&D) presents unique challenges, largely due to the specific demands of the field environment. These challenges hinder the effective deployment of AI solutions. Existing management frameworks and data handling limitations also complicate implementation. While AI research in E&D is growing rapidly, a lack of coordination has led to inefficiencies and duplicate investments.

E&D data typically has big data characteristics—large volume and diverse sources—but it's not yet fully integrated or "big data-ready." Issues with inconsistent data standards, varying quality, and limited data sharing hinder a robust foundation for AI applications. Additionally, a lack of clarity in the objectives, technical pathways, and foundational theories for integrating AI with oil and gas further limits progress. To fully realize AI's potential, future efforts must aim to revamp management processes, enhancing quality, efficiency, and cost savings.

A. Future Directions for AI in Oil and Gas

AI technology has the potential to revolutionize the oil and gas value chain in three primary areas:

➢ Intelligent Equipment: Advances in deep learning, NLP, speech recognition, and reinforcement learning are transforming industrial robots for high-risk tasks like pipeline monitoring and deep-water operations. UAVs are increasingly used in geological surveys, surveillance, material transport, and rescue efforts. Incorporating IoT, machine vision, and deep learning into intelligent equipment will further reduce costs and improve operational efficiency.

➢ Automated Data Processing and Interpretation: AI has already shown promise in tasks such as logging interpretation and reservoir prediction. Emerging technologies like deep learning and ensemble learning are enhancing AI's image processing and predictive analysis capabilities. This progress enables automated interpretation of petrophysical data, seismic images, logging curves, and production data.

➢ Professional Software Platforms: Specialized software is essential for advancing AI in E&D, providing a crucial research tool and competitive edge. AI-enhanced platforms like Petrel, Techlog, and Eclipse incorporate machine learning and data mining, enabling data sharing and collaborative research. Continued AI R&D will further develop these platforms and foster the creation of new software for evolving industry needs.

B. AI Development Priorities in E&D

Scaling up successful AI pilot projects will accelerate adoption in E&D. Key priorities for the next five years include intelligent basin modeling, advanced image-logging tools, nodal seismic acquisition, intelligent directional drilling, enhanced fracturing, and real-time zonal monitoring. While digital basins have been established internationally, China has yet to standardize their development. By focusing on practical applications and refining AI models, China can move closer to achieving unified standards and expanding digital basin technology.

➢ *Future Developments in Oil Exploration and Development (E&D)*

In the next five years, Chinese professionals will utilize big data and AI technology, drawing from E&D achievements in both domestic and international mature basins, to analyze the entire lifecycle of exploration and development. The objective is to create an intelligent decision-making system that can predict the spatial distribution of remaining high-quality oil and gas resources and clearly outline exploration priorities and goals.

- Intelligent Logging: The overseas Scanner 3D scanning imaging series is comprehensive and widely used. Domestically, the EILog rapid imaging system is applied at scale, with prototypes for full-domain imaging and imaging while drilling available. However, there remains a notable gap in stability, reliability, and practicality compared to international standards, and current AI systems do not fulfill industrial-scale application requirements. Future advancements should concentrate on R&D for robust and reliable rapid intelligent imaging logging tools to achieve products that meet world-class standards.
- Intelligent Geophysical Exploration: High-precision results depend on acquisition technologies that are robust in bandwidth, cost-effective, and efficient. Currently, both domestic and international nodal acquisition systems depend on local storage and analog circuit geophones, which restrict frequency bandwidth. Future efforts should prioritize the development of digital nodal acquisition systems and integrated systems (combining vibrational and electronic methods) to create intelligent nodal systems capable of approximately one million channels for onshore applications and for deep-sea operations at depths of around 1,000 meters.
- Intelligent Drilling and Completion (D&C): Significant advancements have been made overseas in multi-size steering tools that offer various modes and angle-building capabilities, making them suitable for D&C operations in China's mountainous regions and loess plateaus. Future development should emphasize R&D for a complete suite of high-power electric-drive fracturing equipment, intelligent life cycle management systems, and smart fracturing solutions to enable "small volume, high-power, and intelligent" fracturing operations.
- Intelligent Oil Recovery: Domestic oil fields primarily rely on water flooding, a method that is more advanced than its international counterparts. However, due to the strong heterogeneity of terrestrial sedimentary layered reservoirs, overall recovery remains low, particularly during high water cut stages. Implementing refined and intelligent zonal injection and production strategies is crucial for enhancing recovery rates. Future development should focus on creating real-time monitoring and control technologies for intelligent zonal injection and production, as well as intelligent integrated reservoir-engineering optimization systems.

C. Recommendations for AI Development and Application

Combining short-term and long-term strategies is vital for maximizing AI's potential in the industry. Successful case studies should serve as models for broader AI adoption. A comprehensive approach to top-level design, data management, R&D deployment, talent development, and value enhancement is necessary to achieve collaborative innovation.

➢ *Short-Term Strategy:*

Strengthen understanding and foster learning, particularly among management levels. Building an effective AI application environment should prioritize business applications, fundamental research, gradual dissemination of individual successes, and the establishment of supportive management systems. Key focus areas should include:

➢ *Strengthening Top-Level Design:*

From an industry-wide perspective, it's essential for academicians, senior managers, and experts to collaboratively develop a unified proposal. This will encourage major oil companies to align their understanding and coordinate effectively, leveraging the advantages of China's socialist market economy. At the enterprise level, management should adopt a business, problem, and goal-oriented approach while facilitating integrated design and dissemination. This will promote smooth data flow, reconstruct business processes, and drive innovation and transformation in management practices. Lastly, in terms of disciplines, equal attention should be given to both software and hardware, guided by practical applications to promote mutual enhancement of research and real-world applications.

D. Improving Data Management

Having a large amount of data does not automatically mean having "big data." Standardized data and sample libraries are critical for effective AI applications. Therefore, prioritizing data management is essential. We need to unify data labeling, improve data interoperability, and strengthen our overall data management practices. This will help create a trust mechanism for data handling and encourage the normalization and compliance of data sharing.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24NOV818

➢ *Enhancing Talent Development*

At present, there is a disconnect in communication and understanding between AI algorithm engineers and oilfield engineers. Furthermore, during the transition from digitalization to intelligentization, we encounter the issue of "building more but utilizing less." The cultivation of interdisciplinary talent is also challenging due to the broad range of disciplines involved in both petroleum E&D and artificial intelligence. To overcome these challenges, we should promote closer collaboration between universities and petroleum companies, as well as between oil firms and IT enterprises, to nurture the required talent.

➢ *Promoting Collaboration and Sharing*

Establishing innovation consortiums that are cross-industry, cross-enterprise, and cross-discipline is essential to facilitate diverse integration among oil companies, between oil firms and IT enterprises, and across various fields. Such collaboration will contribute to the creation of a robust AI technology R&D system for China's petroleum industry.

➢ *Securing Intellectual Property Rights on Algorithms*

With ongoing informatization efforts, the extensive data generated within the oil and gas industry has become increasingly manageable. Additionally, networks and nodes provide a degree of computational support. It is vital to initiate research on foundational algorithms and secure an algorithmic framework with independent intellectual property rights to facilitate the intelligent transformation of the oil industry.

V. CONCLUDING REMARKS

The application of artificial intelligence in petroleum E&D is still in its infancy and has yet to produce groundbreaking results, but the potential is significant. Current achievements can be categorized into three main areas: First, there is the preliminary adoption of intelligent equipment such as UAVs and robots, which are beginning to replace human workers in tasks like pipeline monitoring and oversight of unattended platforms. Second, big data, machine learning, and other IT technologies are being utilized for data processing and analysis in exploration and development. However, progress is currently marked by isolated successes rather than widespread advancements. Third, many companies are recognizing the importance of data sharing and have initiated the development of integrated analysis platforms and software.

Presently, AI applications in petroleum E&D are primarily focused on logging processing and interpretation (such as lithology identification and curve reconstruction), seismic processing and interpretation (including first break picking and fault identification), real-time control of water flooding, and production forecasting. The integration of intelligent algorithms has enhanced the functionality of analysis software, and the introduction of embedded chips has improved intelligent equipment. It is crucial to maintain a clear relationship between the input and output of algorithms, as AI heavily relies on big data. However, the complexities and variabilities of reservoir conditions complicate E&D operations, often resulting in multiple solutions and small sample sizes, which obstruct the broader application of AI.

The deployment of artificial intelligence in petroleum E&D should gradually progress from individual applications to a more industry-wide adoption, rather than attempting an immediate full-scale rollout. Future AI advancements in this sector should focus on technologies such as digital basins, rapid intelligent imaging logging tools, and real-time monitoring of zonal injection and production.

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ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24NOV818

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