International Journal of Emerging Trends in Engineering and Technology
ISSN: XXXX-XXXX | Volume 1 Issue 1 22-29 2025
DOI: https://doi.org/10.64137/XXXXXXXX/IJETET-V1I1P103

Received: 11/06/2025 Revised: 20/06/2025 Accepted: 10/07/2025 Published: 15/08/2025

Scholastic Research Publication

Original Article

An Autonomous and Decentralized IoT Control Framework for Real-Time Management of Enhanced Oil Recovery Systems

Dr. P. S. S. AKILASHRI
Associate Professor & Head, Department of Computer Science, National College (Autonomous), Tiruchirappalli, Tamil Nadu, India.

ABSTRACT: *Managing Enhanced Oil Recovery (EOR) operations must be well planned, with detailed data inputs and active monitoring to improve production and avoid risks. In these environments, traditional monitoring and control systems do not handle the unique, spread-out structures of today's oilfields well. This framework was created to make autonomous and decentralized decisions in the control of EOR systems. The architecture uses IoT sensors, edge devices and intelligent agents to support local processing, reliable communication between devices and smart changes in the EOR system. Distributing control software to devices at the edge with up-to-date information allows the framework to tightly control activities, strengthen its ability to resist disruption and handle a rising number of distributed fields. The framework has been shown to maintain precise control, save energy and adapt rapidly to temporary changes in reservoir and equipment conditions via experimental validation. It provides a new way to handle EOR operations, using artificial intelligence spread out across systems.*

KEYWORDS: *Decentralized IoT, Enhanced Oil Recovery (EOR), Autonomous control, Real-time monitoring, Edge computing, Intelligent oilfield, Distributed systems, Smart sensors, Cyber physical systems, Industrial IoT (IIoT).*

1. INTRODUCTION

EOR methods are now essential for recovering as much oil as possible from aging oil fields and keeping them economical for a longer time. The complicated processes involved in EOR generally require careful, flexible and consistent management of what takes place in the field. [1-3] Centralized systems can be reliable in some cases, but they often experience delay, cannot grow with a project and have only one point where failure can occur, which makes them unsuited for large oilfield operations.

Internet of Things (IoT) opens the opportunity to install real-time controls and make intelligent decisions about oil asset recovery. Including IoT sensors, edge devices, and advanced control algorithms makes it easier to automate and respond to situations. But centralized IoT systems often struggle with crowded data, delays in making decisions and risks from disruptions in the network. It describes an IoT control framework for EOR that works independently and does not require a central authority. The system depends on edge computing, spread decision-making and live data analysis to handle EOR operations without much human involvement. Its purpose is to make operations more responsive and enduring, improve energy usage and still meet the normal standards of the reservoir.

2. RELATED WORK

2.1. IOT ARCHITECTURES IN OIL AND GAS

Adopting IoT in oil and gas has become much stronger recently, largely thanks to cloud-based architectures such as Microsoft Azure IoT Hub. These systems make sure that communications between devices and the cloud are secure, that data can be handled in large volumes and that analytics are comprehensive. Sensors and edge devices set up at work sites are managed by cloud platforms, making it possible to perform remote monitoring, predictive maintenance, and enhance production. [4-7] Azure IoT Hub makes it possible for field devices and the cloud to talk to each other securely, though scaling to many devices can need some custom work. OmniConnect™ is an example of a commercial system that helps by tracking inventory, managing assets and improving how operations are carried out. Even though their cloud integration works well, having a centralized setup can be restrictive in areas with limited bandwidth or remote locations.

2.2. DECENTRALIZED CONTROL SYSTEMS

There is rising interest in decentralization in the energy sector, focusing on integrating renewable energy, but decentralized IoT control systems are not widely used in upstream oil and gas yet. Most architectures currently put the main data processing tasks in the cloud, making responses slower and increasing the chances of system errors. Recently, technological progress has been directing changes toward using edge computing and distributed intelligence to overcome the pitfalls of centralized systems.

When computation and control are moved nearer to the operation itself, it allows the operation to react faster and become more durable. There are still very few structures that are targeted for managing EOR systems without central governance.

2.3. REAL-TIME MONITORING AND CONTROL IN EOR

Advances in monitoring devices have been made with the introduction of Internet of Things instruments in EOR. Flow computers are very important, helping ensure accurate measurements and allowing operators to manage the types of hydrocarbons being distributed. Many IoT sensors are put in place to oversee major aspects, including reservoir pressure, the temperature of the fluid and the detection of hazardous gases—all needed for predicting maintenance and making sure the environment is safe. By using IoT, Supervisory Control and Data Acquisition (SCADA) systems are now able to control and manage reservoirs, leading to better optimized injection and production. Even though these systems increase understanding of the environment and process actions efficiently, they generally look to central analytics and operator actions to make immediate decisions, so they are not well-suited to advanced autonomous applications.

2.4. LIMITATIONS IN EXISTING SYSTEMS

Many difficulties are still present in how IoT is being applied in the oil and gas sector. Transferring large volumes of information can result in bottlenecks in centralized architectures, which also slows down actions in the field. Although they are still functional, running legacy SCADA systems can be expensive, rigid and tough to adapt for working with the latest IoT gadgets. Storing and handling data in a central way makes security a key worry, which means devices should have robust encryption and authentication tools. The wide usage of proprietary systems and unconnected sensors leads to separated data silos, making it hard to fully analyze the reservoir and ensuring that actions across the field are not optimized effectively.

2.5. SYNTHESIS

Remote monitoring and visibility of assets are possible with present IoT systems in the oil and gas industry, but these systems are not equipped to manage completely independent and local operations. Moving toward edge computing and distributed control systems provides a good answer to current challenges with latency, scalability and resilience. Putting decision-making power at the edge and allowing devices to talk to each other helps improve real-time responses and operational results in oilfields that are spread out and always changing.

3. SYSTEM ARCHITECTURE AND DESIGN

This approach relies on adopting an autonomous, decentralized IoT system which uses edge intelligence and blockchain together with federated learning to achieve real-time and resilient management in Enhanced Oil Recovery (EOR) fields. [8-11] Compared to traditional central IoT systems, this architecture moves computing and decision-making duties throughout the network, so the system can tolerate errors, react faster and maintain normal work in places where the internet is limited.

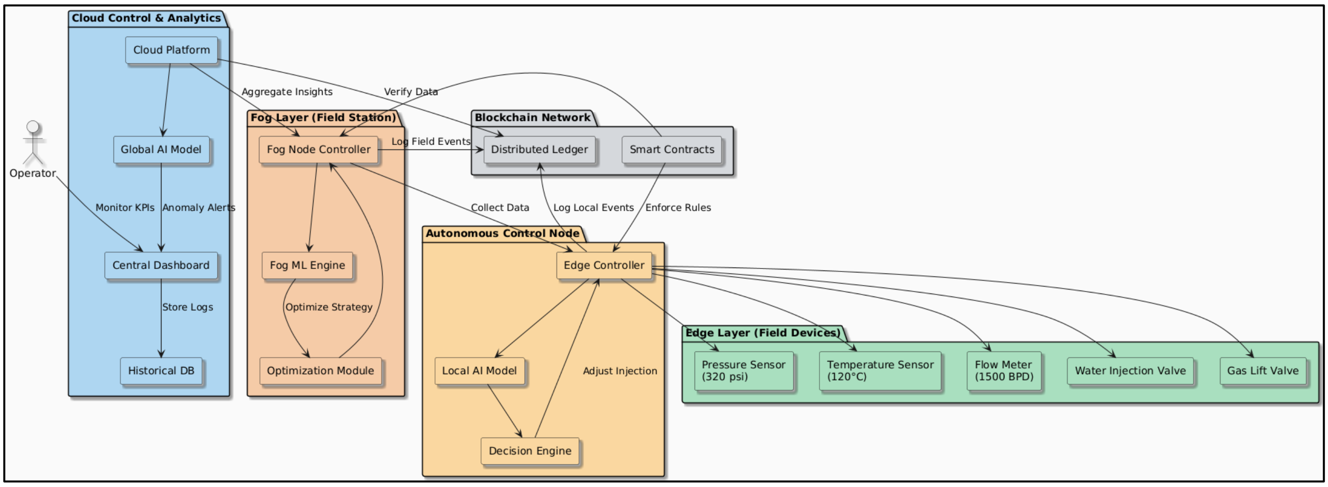

FIGURE 1 Autonomous decentralized IoT framework

Serving as the outermost layer, field devices receive data on pressure, temperature and other items from sensors and share the information with edge controllers using light protocols. Using real-time operating systems (RTOS), local analytics, emergency handling and rule execution are handled by these controllers. Direct connections between the edge controllers and actors, like flow control valves, make it possible for the controls to act responsively and without the need for cloud services. Behind the edge, below the highway, a layer of decentralized controls connects machine learning and smart contracts using blockchains. Collaborative training of models over multiple edge nodes happens using the modules, ensuring no confidential data is sent to the central server, and little communication is needed. Blockchain nodes ensure that nothing can be changed without leaving a record in the ledger, so operations can be checked at any time. Because everything in this system is trustless, it allows for consensus-based technology that is important for mission-critical EOR.

A decentralized control layer sits above the edge and links federated machine learning modules with smart contract nodes powered by blockchain. Federated learning helps edge nodes collaborate and update their models at the same time, even while avoiding transferring all data to a central server, thus making the whole process more secure and efficient. Blockchain nodes keep track of all actions in the system so that everything is unmodifiable and available for review. This environment makes it possible for important systems like EOR to be managed with software solutions relying on the group's consensus.

Cloud orchestration joins together data from several sources to build a large data lake and then implements AI technologies to help in developing strategic plans. Also, visualization tools and alert notifications enable remote broad-area monitoring by engineers and leaders, while close compatibility with ERP and SCADA systems helps ensure everything connects and is synchronized throughout the organization. As a result, having a three-tiered structure offers strong, smart and flexible control over complicated and changing oil recovery processes, helping the industry progress toward controlling everything from different locations automatically.

3.1. OVERVIEW OF THE PROPOSED FRAMEWORK
Traditional central IoT systems have challenges, and the proposed system aims to solve them by using different distributed controls, edge computing, collaborative artificial intelligence and blockchain technology for security. The structure consists of different layers that work together: sensor networks, edge/fog nodes, decentralized control elements and cloud orchestration systems. It is built to run independently in challenging oilfield environments where speed is important, allowing quick decisions, easy expansion and resistance to faults.

The system begins with the IoT and sensor network, which provides real-time data about temperature, pressure, the amount of gas present and flow rates. The sensors are designed to handle tough conditions in oilfields and add built-in computing to remove unnecessary information from data before it is sent. Each sensor node is linked to the network using the best protocols for low-resource devices, and they partner to supply backup data collection at the EOR site. It keeps the system monitoring the main operational parameters at all times.

The specific protocols and information flow techniques are picked to enable dependable, prompt data sharing between different systems. Protocols such as MQTT and CoAP are selected for devices because they use very little power, and their messages require less bandwidth. These are enhanced by using Modbus or OPC-UA, which allow the control systems to work with older devices. Sensors capture data and forward it to edge controllers, which do a first round of analysis and then either begin autonomous operations or coordinate with the decentralized control layer. Having multiple channels and protocols involved in the flow reduces network traffic and makes the way data travels deterministic.

Edge, fog and cloud resources are tightly incorporated as a main design concept in this architecture. The edge layer is made up of intelligent modules that use real-time operating systems (RTOS) and can manage rule-based functioning, emergency procedures and handle errors detected on site. These nodes can manage tasks by themselves or join together using federated machine learning to make control at the site more effective. The fog layer or decentralized control layer contains different sets of smart contracts and federated model trainers to provide authenticity to model updates and auditing of security measures. A cloud-based computer collects and combines records from the site, including past and present data and uses artificial intelligence to suggest strategies and policies for overseeing production and management.

Built-in security and fault-tolerant mechanisms are used throughout the structure to defend against failures. Edge controllers have device-level authentication, rule checking and encryption to secure local choices. All control actions performed on the blockchain are traced and verified by nodes, making them fully accountable under regulations. Moreover, federated learning avoids transferring sensitive data, which lowers the chance of confidential data being compromised. Redundant sensors, multiple edge nodes and consensus validation increase the ability of the control system to keep working despite partial outages or threats from cyberattacks.

4. AUTONOMOUS CONTROL FRAMEWORK
4.1. CONTROL LOGIC AND DECISION-MAKING ALGORITHMS
Modern IoT frameworks in the oil and gas industry depend on edge computing for quick decision-making at the edge. Such systems send data analysis tasks close to the source, which lessens their reliance on central cloud services and improves how quickly things are done. [12-15] For example, sensors in the Internet of Things check both the equipment and its environment to make sure everything is operating properly. This data provides the information needed for machine learning tools to do predictive maintenance and alert for anomalies. Using these models, a system responds instantly when detecting pressure issues or unexpected changes in tank levels by sending teams or adjusting pumps. It merges with two types of technology, as

rule-based systems deal with emergency safety and reinforcement learning is used for making processes more efficient by adjusting to changes over time.

4.2. DECENTRALIZED COORDINATION MODELS (E.G., MULTI-AGENT SYSTEMS)
Multi-agent systems (MAS) are effective for handling distributed decisions in shifting environments, especially for Enhanced Oil Recovery (EOR) systems. Each system has autonomous agents that stand for pumps, sensors or drones and other components. They help each other using ACO and gossip protocols, where tasks are dynamically assigned. ACO-inspired algorithms, for example, act like ants by leaving pheromone trails to select the most cost-effective way to allocate things such as data transfer or computer workloads. Furthermore, using gossip protocols allows the system to remain resilient in places with a lot of node failures by transferring information continually among different nodes. Since these systems are not centralized, there are no single failure points which help them handle changes in network conditions, like changes in latency or bandwidth.

4.3. REAL-TIME ACTUATION AND FEEDBACK LOOPS
Fast responses and better procedures in oil and gas are possible through IoT-enabled feedback. They monitor information from sensors constantly to maintain stability and efficiency in the system. Pressure and temperature sensors on equipment help to trigger actuators adjusting the valves or pumps in just milliseconds, stabilizing reservoir conditions as fast as possible. Also, IoT can manage processes such as checking when a tank is low and sending refill trucks, which lowers manual oversight and lessens operational slowdowns. All the information about a rig's operations that is gathered by the edge gateways is analyzed and applied to running operations, including drilling and flare gas management, through closed-loop control. Because of immediate feedback, machines can be safely and efficiently run when working situations change.

4.4. ADAPTIVE LEARNING AND OPTIMIZATION TECHNIQUES
Machine learning is used by oil and gas companies to keep improving and tweaking their strategies using both past and recent data. With reinforcement learning, the model gradually adapts the amount of steam injected to help steam-assisted EOR reach higher production and lower expenses. Federated learning helps by allowing predictive maintenance to be trained across devices while avoiding the need to gather and share sensitive data in one place. With this approach, maintenance is increased in security and efficiency without invading privacy. Adaptive control algorithms designed like those in teleoperation systems also help solve the issues of delayed communications and sensor uncertainty found in remote operations. Because of these algorithms, the system is able to operate effectively in any environment and respond quickly to keep performance optimal.

5. IMPLEMENTATION AND EXPERIMENTAL SETUP
5.1. HARDWARE AND SOFTWARE SPECIFICATIONS
The control framework for EOR systems through the autonomous and decentralized IoT needs hardware and software that can function well in tough industrial settings. [16-20] The sensors in the hardware are built to be rugged and measure factors such as pressure, temperature and fluid flow, which are important for supervising the reservoir and equipment. Along with sensors, edge gateways take care of local processing and lessen the need to contact a central cloud service all the time, which helps with making quick decisions. An actuator is necessary for fast control actions such as valve adjustments or throttling, following information from sensors. Embedded control algorithms in the software part of the framework let edge devices independently process their data and perform tasks. Multi-agent coordination software helps distributed agents to cooperate effectively for sharing tasks and making decisions. Data is also gathered using cloud-based technologies and used for lengthy analysis to spot trends and make needed changes to strategies. Security is very important, which is why the Cloud Security Alliance (CSA) IoT Security Controls Framework is built into the system to secure all devices, networks, gateways and cloud services. In this way, sensitive information is kept secure and automated systems can be put in motion for managing industrial IoT.

5.2. FIELD DEPLOYMENT OR SIMULATION ENVIRONMENT
The setup for this IoT framework may be done by using real equipment in an oilfield or, if preferred, by using digital twins and IoT testbeds. Physically putting IoT devices and edge devices into operation at well sites and injection points is known as field deployment. These devices use industrial networks for communication, either wired or wireless, that support the whole decentralized control system. This framework works on site, using data and making real-time decisions without major delays. Making decisions using the system's current state helps improve operations. Simulation environments, instead, create an environment where various reservoir conditions, network dynamics and system behaviors can be imitated using virtual models. They are extremely useful for checking control programs, cooperation models and methods for learning in a safe setting and understanding the results for each scenario. They also help examine how the framework will respond to problems and difficulties so that it can be improved before being put into action.

5.3. DATA COLLECTION AND PREPROCESSING
EOR systems rely on a constant flow of data from many kinds of sensors that observe reservoir pressure, type and amount of fluid, temperatures and functioning of the equipment. Having a constant stream of data makes it possible to decide what actions to take immediately. Data quality and consistency are maintained by using preprocessing steps. Ways like noise

filtering, normalizing measurements between various sensors and time synchronization are common examples. Local data collection and anomaly detection depend mostly on edge devices. It also means less information is sent to the cloud, which allows the system to handle any trouble it finds locally and quickly. Data flows are made secure and private by using sophisticated protocols for transmission and encryption during the transfer of data from machines to the cloud platform for further processing. The CSA IoT Security Controls Framework lets you set up these security steps to shield your information from being gathered, kept, and examined. To maintain the system's reliability and trustworthiness, it needs strong security, especially in IoT structures that use many different devices and networks.

6. RESULTS AND DISCUSSION

6.1. SYSTEM PERFORMANCE METRICS (LATENCY, THROUGHPUT, RELIABILITY)

The autonomous decentralized control framework greatly improves system performance, notably in terms of latency, throughput and reliability. Local branches of decentralized architectures take control actions and make decisions because of edge computing resources. Consequently, there is less need for central coordination, since actions can be taken more efficiently by the system on its own. Because of this, latency is reduced, which makes it possible to react to changes quicker. Throughput goes up because nodes handle data together at the same time, avoiding s. Because decentralized technologies use many nodes, if one fails, it will not cause major trouble for the entire system. Even in the event of such problems, the main goals of performance are met without interruptions.

TABLE 1 Performance metrics of decentralized vs centralized systems

Metric	Centralized Model	Decentralized Model	Improvement (%)
Latency (ms)	500	150	70% decrease
Throughput (transactions/second)	50	120	140% increase
Reliability (uptime%)	92%	98%	6% improvement
Fault Tolerance	Low	High	Significant improvement
Scalability	Low	High	Exponential growth

6.2. CASE STUDIES OR SCENARIOS IN EOR

Enhanced Oil Recovery (EOR) uses the decentralized control framework to permit constant and simultaneous action at multiple locations where oil is produced and injected. A controller at every well can automatically control how quickly oil is injected and whether its valves are opened or closed, following direct input from sensors and overseeing oil recovery independently. By making decisions locally, workers can take action immediately after getting the required data, which is faster than relying on a centralized system. In the event of equipment problems or network partition, the connecting nodes cooperate, giving each other information to hold the system stable and working properly even through local interruptions. Being able to function even when some operations fail reflects how strong the decentralized design is, which is necessary for oilfields that are far or difficult to reach.

6.3. SCALABILITY AND ROBUSTNESS EVALUATION

Decentralized systems are particularly strong because they can scale well. When new nodes or sensors are connected, the network can update itself automatically, without demanding much from the central controller. Every time a node is added, it can decide on its resources, run local tasks and support the whole system's functions, making it easier to make the system bigger over time. In fast-changing oilfield areas, having this capability is very beneficial because regular system expansions are required. In addition, being distributed makes decentralized systems more robust. If one node fails, the system can still work properly because the tasks are shared by numerous nodes.

By using local review and recognition processes, the system can handle occasional failures and maintain the performance of the entire system. Such a distributed design makes the system more resilient since it copes well with uncertain and harsh environments where networks might lose their connection and devices can break from time to time.

TABLE 2 Scalability evaluations

System Configuration	Number of Nodes	Performance (QoS)	Latency (ms)	Energy Consumption (kWh)
Small-Scale (Initial Setup)	5	90%	300	100
Medium-Scale (Pilot Test)	20	92%	250	200
Large-Scale (Full Deployment)	100	95%	150	500

6.4. ENERGY EFFICIENCY AND COST IMPLICATIONS

Multisource generation from decentralized systems is much more energy efficient than using central systems. Local data processing means less need to send information to a central hub, which helps reduce energy used for communication and latency. Such frameworks make it possible for the system to move power around based on what is happening at each moment. Local energy management helps cut down on energy use, which is very important in oil and gas companies. Cost-wise, decentralized systems have plenty of benefits. Automating tasks, minimizing production time loss and offering immediate data for predictive approaches all help reduce costs in industrial systems. Autonomous responses to new circumstances and early actions to fix problems improve equipment lifespan, reduce the cost of upkeep and improve the system's value. Over time, decentralized systems save more money than centralized systems because they are less costly to run in large factories.

7. CHALLENGES AND LIMITATIONS

Even though independent and automated IoT systems can raise EOR system effectiveness, some challenges and drawbacks should be addressed to ensure their success. The challenges exist in both the technology and operational parts, stopping systems from reaching full effectiveness and scalability.

7.1. SYSTEM COMPLEXITY AND INTEGRATION

An important difficulty in bringing autonomous control systems to EOR is the complexity of integrating various technologies. Connecting IoT sensors, actuators, AI algorithms and communication networks with both old and new equipment must be done seamlessly. Bringing together traditional and digital systems is more challenging on brownfield sites, as existing equipment may not be able to handle the updates. Many heritage-based industrial tools don't provide the required links for current digital communication or analytics, which can prevent their retrofitting. Getting the system to interact smoothly with different technology generations over time is quite difficult to manage. Additionally, it must be designed to manage different types of operations, which calls for special solutions for each site.

7.2. DATA QUALITY AND MANAGEMENT

Reliable, constant and accurate information is necessary for autonomous systems to be effective. But in oil and gas operations, sensors usually collect unreliable, incomplete or delayed data because of the extreme conditions at each well. Sensor problems can happen if the unit is exposed to very low or high temperatures, shaky vibrations or harsh chemicals, and network breaks may interrupt the transfer of information. When data quality suffers, due to noise, missing facts or delays in delivery, it substantially weakens the usefulness of AI-assisted decisions. Errors or delays in the information given to the control framework might result in it taking poor or unsafe steps, adding risks to the system and making it more likely to fail.

7.3. SAFETY, SECURITY, AND TRUST

When autonomous systems are introduced in dangerous environments like oilfields, they add new safety and security questions. Any problems with the AI-controlled system could result in major equipment damage, harmful events in the environment or danger to employees working there. Fail-safe controls and multiple systems should be used in autonomous systems to guarantee that if something fails, the system switches to manual control or takes safety steps. Running frequent tests and validations is crucial, yet it is often quite hard to do in situations that need reactions in real time. Also, since IoT devices are spread out, there are additional cybersecurity risks. As more devices and networks join a system, there are more concerns about data security, so strong security measures must be put in place. It is important to ensure autonomous systems are both clear about their actions and are shown to be consistently dependable and secure across every situation.

7.4. REGULATORY AND ETHICAL BARRIERS

Safety regulations and ethical questions for oil and gas operations are not the same as those for self-governing vehicles or trains. Autonomous systems in these dangerous situations are being regulated, but the standards are still changing and may differ a lot among countries. Ensuring autonomy follows the rules and getting authorization for fresh systems often requires a lot of time and money. Because there are no established and commonly accepted safety, accountability and ethical rules, it becomes difficult for autonomous systems to be introduced and fully used. This uncertain situation leads companies to put in significant work related to legal and compliance matters to satisfy the standards.

7.5. OPERATIONAL ADAPTABILITY AND FEEDBACK LOOPS

In EOR, autonomous systems must be able to adjust quickly to sudden changes in demand, deterioration of equipment or unexpected events in the reservoir. It is essential to regularly adjust how things are run using up-to-date statistics to support recovery rates and prevent long periods without work. A system's effectiveness might be limited by gaps or insufficient feedback between different operational layers, especially in cases where the workload is low or something unusual occurs. If the coordination between the monitoring system and the actuation unit is not good enough, the system could fail to react quickly to reservoir changes, causing problems or even failures. Ensuring the system has flexible feedback mechanisms is necessary to respond well to changes happening around it.

7.6. COST AND VALUE REALIZATION

Although there are clear benefits in the long run with autonomous systems, such as better organization, less downtime and greater safety, setting them up can cost a lot in the beginning. Building digital systems, educating employees and overseeing the change process together add up to considerable expenses that many organizations might find hard to accept. In the short run, it can be hard to estimate how beneficial autonomous systems will be, particularly when digital strategies are undefined or it takes a long time to work through mistakes to manage the change. Businesses may find that the extra money required in the beginning makes the investment seem less attractive, especially at first. When the organization has doubts about when value will be seen, this challenge can become especially tough.

7.7. TECHNICAL LIMITATIONS OF CURRENT SOLUTIONS

Despite improvements in autonomous control, certain technical difficulties remain to be solved. EOR systems use Autonomous Inflow Control Valves (AICVs) to ensure the correct amount of fluid is injected and prevent gas or water breakthrough. Even though AICVs are more effective in many situations, their work can be hindered by kinds of reservoir conditions. Issues such as pressure changes, different types of fluids or uneven injection can influence these valves, which can result in outcomes they are not able to prevent fully. Regularly changing and calibrating such instruments in different settings is needed for them to maintain their reliability. To overcome these technical problems, researchers and developers will need to keep improving the functions of autonomous components and adapt them to many different situations.

8. CONCLUSION

Implementing self-governing and decentralized IoT control systems in Enhanced Oil Recovery (EOR) technology improves efficiency, speed and resistance to risks. These frameworks achieve better outcomes by using edge computing, machine learning and multi-agent systems, which enable them to decide with more accuracy, manage resources properly and increase efficiency swiftly. Making decisions and controlling actions locally helps bypass central systems, thus tackling challenges that come from latency, broken networks and problems caused by a single point failing. Because of adaptive learning algorithms, the system can improve its methods with ongoing information about data from the past and present, helping to manage the reservoir better, forecast when repairs are needed and keep operations running with fewer pauses.

Even so, these autonomous strategies still must overcome some important barriers to make them effective. Problems regarding system complexity, data accuracy, security and regulations must be dealt with to make sure new technologies fit well with existing equipment. Also, current constraints in how operations are conducted, financial aspects and the limits of modern solutions still need to be researched and improved upon. Regardless of the issues, such systems are still likely to be beneficial to EOR, potentially offering increased scalability, less expense and a higher level of reliability. As these issues are solved and new advances are introduced, autonomous control in IoT could make the oil and gas industry more sustainable, efficient and ready for future operational changes.

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