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Remote Operation Support Based on Wearable Augmented Reality: Challenges and Field Deployment

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Abstract

In response to the evolving demands within the oil and gas (O&G) industry, this paper examines the integration of augmented reality (AR) headsets in remote operation support, focusing specifically on the challenges encountered, field deployment strategies, and considerations for global scalability and ongoing technology development. Four case studies—remote equipment surveys and troubleshooting, tubular thread inspection, field auditing, and rig site operations—are presented to demonstrate how these technologies can enable feasible solutions for remote support and collaboration, which transform traditional operational paradigms. By leveraging AR and related remote technologies, operational efficiency, safety, and cost-effectiveness are enhanced. However, the implementation of AR in harsh and remote environments introduces unique challenges. Key obstacles, including environmental conditions, connectivity limitations, data security, ergonomic constraints, and user adoption barriers, are highlighted and addressed through various mitigation strategies. For example, ruggedized and explosive atmospheres (ATEX)--compliant AR devices were deployed to withstand tough environmental conditions at drilling rigs. To manage connectivity issues in remote locations, private networks, and encryption protocols were implemented to ensure secure, stable communication channels necessary for real-time support. Comprehensive user training programs were introduced to facilitate smooth adoption and to deliver practical benefits to users. In addition to addressing these challenges, the impact of global deployment strategies and continuous technology development on maximizing the effectiveness of AR in the O&G industry is outlined. Significant operational improvements are indicated by the findings from these case studies, including a reduction in travel-related expenses and carbon emissions, enhanced accuracy in remote inspections, improved safety protocols, and decreased maintenance costs. These results underscore the transformative potential of AR when thoughtfully implemented with robust support systems, highlighting its ability to drive productivity and sustainability in O&G operations globally.

Our findings suggest that AR, paired with comprehensive challenge mitigation strategies, offers a valuable model for future applications across the industry. With continued advancements in wearable

technology, remote support can further evolve to meet the industry's demands for operational efficiency, safety, and environmental sustainability.

Introduction

AR technology is rapidly transforming operations across various sectors, and the O&G industry is no exception. Its applications span various areas, such as project planning, communication and collaboration, remote assistance, training, and real-time data visualization. As companies recognize its significant advantages, AR is increasingly adopted for remote inspections and maintenance tasks, employee training, quality control, asset management, and so on. In response to industry demands for affordable and scalable solutions, many companies are attempting to use AR to fill workforce gaps, streamline complex processes, and improve production quality (Osborne & Mavers 2019).

In O&G industry, AR has gained more attractions for improving operational efficiency, reducing costs, enhancing worker safety, and transforming industrial operations (Masoni et al. 2017). With advancements in technology, including mobile devices and AR headsets, AR's role in digitalizing O&G is growing (De Paolis & Bourdot 2019), and is becoming essential in the manufacturing industry, improving communication, information sharing, and safety (Yeom et al. 2024). Additionally, AR can enhance the learning experience by providing interactive and immersive educational content, which can lead to better retention and understanding of complex subjects (Wanasinghe et al. 2021). AR in training and education can also help bridge the skills gap by providing hands-on experience in a controlled environment (Khan 2024). Furthermore, AR has proven practical in reducing maintenance time and errors by delivering step-by-step instructions directly to technicians' fields of view (Dash et al. 2021). This capability enables real-time remote guidance, reducing travel costs, improving service quality, and supporting sustainability goals by decreasing CO_2 emissions (Yeom et al. 2024; Alahmari et al. 2019; Siwei et al. 2024). Additionally, AR simplifies technical manuals, making procedures easier and improving technician performance in high-stakes environments (De Pace et al. 2018).

Despite these benefits, AR faces challenges including high bandwidth requirements, latency, user acceptance, visual fatigue, data integration, and security issues (Abramovici et al. 2017; Rejeb 2019; Nazar & Subash 2024). The ergonomic limitations of AR headsets, particularly in limited fields of view, pose safety concerns. Streaming high-resolution AR video, device compatibility, and energy efficiency are additional issues, underscoring the need for new standards, including data security and interoperability, to maximize AR's industrial applications (Rejeb 2019; Nassani et al. 2016). Furthermore, factors such as connectivity limitations in remote areas (Abramovici et al. 2017), high upfront costs, and the need for specialized hardware can hinder large-scale implementation. However, with ongoing advancements in AR technology and communication infrastructure, the potential for AR to deliver significant long-term value is undeniable. As AR solutions continue to evolve, their applications in remote assistance, predictive maintenance, training, and field inspection will likely expand, creating a safer, more efficient, and more sustainable future.

This paper aims to provide insights into the integration of AR technology within the O&G sector by addressing the following questions:

1. What impact does AR have on operational efficiency, safety, and training in the O&G sector?
2. What are the best practices for integrating AR into existing workflows and processes in the O&G industry?
3. What are the main challenges faced by O&G companies when deploying AR technology in field operations, and how can these challenges be effectively addressed to ensure successful AR implementation?

The main contribution of this paper is to summarize the challenges encountered, our solutions, and lessons learned during the AR deployment to our machine shops and drilling rigs by providing empirical insights into the practical applications. Through detailed field case studies and real-world examples, this paper highlights innovative practical strategies that organizations may adopt to effectively integrate AR technologies. Additionally, it addresses specific obstacles related to bandwidth, device compatibility, and user acceptance, offering actionable solutions to mitigate these challenges.

Challenges and Technology Development

Wearable AR technology is not only a piece of hardware for acquiring information from the field but also, more importantly, as a digital platform for remote operation support and process digitalization. Therefore, technology development should include hardware selection, a cloud-based platform, Artificial Intelligence (AI) and Machine Learning (ML) functions, and human-machine workflow integration. Deploying AR technology in the O&G sector presents several challenges. These challenges must be addressed effectively to maximize the potential of AR in improving operational efficiency, safety, and cost savings.

Hardware selection

It is not pragmatic to evaluate every single AR headset. Instead of product-driven tests, we began defining what we need for the rig site and maintenance shop and then chose the appropriate AR headset for field tests. The key specifications are listed below:

- Headset type: there are three main types: (1) fully covered nontransparent goggles, (2) fully covered semi-transparent goggles, and (3) open frame with a near-vision screen, see (Fig. 1). The AR headset that brings additional graphical information may pose safety risks of distractions when used in certain operational scenarios. The restricted vision and potential discomfort from prolonged use can affect workers' awareness of their surroundings and hinder their performance. To mitigate this, we selected the third type to fit for rig and shop operations due to minimized view distraction, compact footprint, and lightweight.

(a) (b) (c)

Figure 1—Different types of AR headsets: (a) cover-all nontransparent goggles, (b) fully covered semi-transparent goggles, and (c) open frame with near-vision screen, which fits the best for field operation.

- Hazardous location: for a rig site application, the explosion-proof rating is required at least IECEx & AEX zone-1 or NEC & CEC Class I Div II. Ingress Protection must be equal to or higher than IP 54 (dust-protected and splashed water in any direction) for outdoor all-weather conditions in offshore & land operations. For shop usage, the requirements are typically less stringent than rig site. We utilized ruggedized AR devices designed for industrial environments: ATEX Zone 1 and Class I Div I, IP66, drop-proof up to 2 meters.
- Operating temperature: the AR headset should function in a wide temperature range from -20°C to +50°C to match the rig crew's working condition. The operating temperature range is not just limited by the sensor & camera but mainly by the battery as well.

- Noise level: The rig floor noise level is typically above 85 dB and could be even higher near the mud pumps or generator sets. The AR headset should have a reliable noise cancellation mode to enable clear communication between the headset user and remote users. On the other hand, the headset can capture machine noise, allowing remote experts to assess environmental conditions and provide more accurate support. To mitigate this challenge, the ruggedized AR we chose has both noise capture and cancellation modes, and we verified both modes worked well at a noisy rig (100dB when near mud pumps).
- Bandwidth requirement: Wi-Fi is a prerequisite to the success of deploying AR headsets. The bandwidth requirement for the AR headsets is set as 1 Mbps for regular remote viewing sessions and 3 Mbps for remote viewing plus video recording. To mitigate this, we employed private networks specifically for the AR devices either via satellite or Starlink in all our locations where available, ensuring robust connectivity even in remote areas. In instances where dedicated connections were not feasible, we utilized ATEX zone-1 rated cellular hotspots for a rig site and sometimes leveraged mobile devices for a shop as hotspots to provide Wi-Fi access.
- Camera specs: The camera sensor is at least 12MP to allow the remote users to view the details such as tubular thread inspection. The AR headset should be able to auto-adjust the resolution depending on the bandwidth. It may use lower resolution for video streaming but higher resolution for still pictures.
- Data security and privacy: we addressed this concern by implementing end-to-end encryption for all video communications and data transfers. Access to the cloud storage, where all videos, photos, and real-time session information are stored, was restricted through Single Sign-On (SSO) authentication, ensuring that only authorized personnel could participate in real-time video sessions and access sensitive data.

Human-machine workflow integration

(Fig. 2) shows a high-level schematic of cloud structure and the integration with operation workflows. The cloud platform is device-agnostic and can support AR headsets, computers, smartphones, and tablets. The rig site applications typically go with ATEX zone-1 wearable headsets due to hazardous location. On the other hand, the maintenance shop may have more choices like a non-Zone-1 headset or a smartphone. If a technician performs a digital workflow checklist, a tablet is better than an AR headset or phone. Besides remote viewing and digital workflow apps, the platform stores all data, images, and videos in the cloud. A dashboard can retrieve data via API (Application Programming Interfaces) and visualize contents and usage metrics. It should be noted that the platform allows company users to join via SSO and third-party users to join in remote view sessions via passcode.

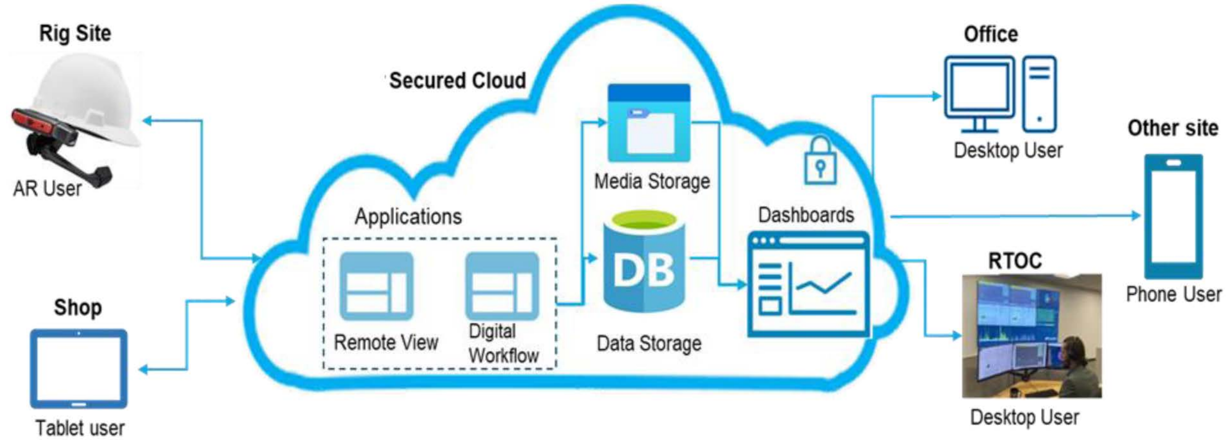


Figure 2—Human-machine workflow integration, where the cloud platform supports not only wearable AR headsets and computers but also smartphones and tablets.

Global Deployment

After the technology assessment in 2022 and initial field trials in early 2023, the project moved to the global rollout phase. As shown in (Fig. 3), the vision is to connect the right resources at the right time and digitalize the operation workflows. To ensure global success, we have adopted the following strategy and received positive field results, as mentioned in the next section.

Figure 3—Overview of field applications at shops and rigs with a goal of connecting the right resource at the right time

Standardized global support model

Although the headset is commercially available, the model directly ordered from OEM (Original Equipment Manufacturer) does not fit the global deployment because the OEM cannot provide customization and training. Together with IT and supply chain teams, we developed a global supply model streamlining AR headset purchasing, device configuration, shipping logistics, user management, training, and maintenance. The procedure has been published internally as a global standard document in the company's Integrated Management System (IMS). As shown in (Fig. 4), this model automates internal processes across different organizations and simplifies users' actions with no need to interface with the OEM.

Figure 4—Standardized global support model automates internal processes across different organizations and simplifies user-side actions

Region-driven incremental rollout

In terms of technology deployment, there are typically two approaches: top-down and site-by-site. Considering the complexity of this project and dependency on local infrastructures, we decided to choose a region-driven site-by-site rollout, i.e., each region decides how many headsets, when, and where to deploy the technology. This approach promotes the ownership of local regions, improves the efficiency of capital investment, and effectively manages user expectations. At the same time, the global knowledge transfer of different use cases is also implemented among quarterly maintenance network and product line meetings. After one year of region-driven incremental rollout, most of the company regions have been equipped with AR headsets and maintained active usage, which can also be tracked in the cloud-based platform.

From shop to rig

For each region or business unit, the maintenance shop is a testing ground before moving to the rig site. The shop site operation may have less operation intensity, hazardous location rating, and internet difficulties. Therefore, any new AR headset model and new functionality will be fully adopted by shop staff first and then to the rig site. The practice has accelerated the learning curve, quickly received feedback, and identified/ resolved potential issues.

Local champions and global knowledge-sharing

Finding the right local lead is one of the key factors to success. Besides general interest in digital technology, the right local champion should have the need for remote operation support, understand the current operations, and assume a certain level of leadership role. Among all the positions we have collaborated with, the Shop Reliability Manager or Rig Maintenance Manager is the most effective candidate for leading the local rollout. Once assigned, the local champions will receive the headsets, complete training, define success criteria, and prioritize the applications. After the initial engagement, the local champion will lead the local deployment and bridge the Technology team and local business unit in terms of field results, improvement requests, and lessons learned. Global knowledge sharing accelerates the learning curve, enables quick iterations in improving the support model, and promotes the rollout in other regions.

Manage cost and optimize return on investment (ROI)

The cost of AR devices and infrastructure upgrades can be a concern, so demonstrating a clear return on investment (ROI) is crucial for decision-makers. We started with a pilot program to showcase the effectiveness of AR devices in our operations. Furthermore, the Technology division provides loaner headsets for some local regions to further verify the business cases. This approach provided tangible data on reduced downtime, decreased travel costs, and improved maintenance efficiency. It also allowed us to define the success metrics and estimate the baseline cost/time-saving.

Success metrics to quantify business value

The Key Performance Indicators (KPIs) including cost-saving and Environmental, Social, and Governance (ESG) metrics are discussed in Table 1. These metrics, gathered through practical implementation and ongoing use of AR tools in operational settings, reflect observed outcomes in areas such as operational efficiency, health and safety, cost management, and sustainability. The following is a comprehensive breakdown of the potential KPIs metrics that companies can track when deploying AR technology, aligning operational improvements with sustainability and governance goals.

Table 1—KPI Matrix for AR in the O&G industry

Category	KPIs	Description
Operational Efficiency	Maintenance Downtime Reduction	Reduction in downtime due to AR-enabled predictive maintenance and remote support.
	Maintenance Efficiency	Increase in first-time fix rates using AR-guided workflows.
	Training Time Reduction	Reduced time for technician training using AR simulations.
Health, Safety, and Environment (HSE)	Incident Reduction	Reduction in safety incidents through AR-enabled real-time hazard detection and guidance.
	Emergency Response Time	Improvement in response times during emergencies with AR-enabled guidance.
Resource Management	Asset Utilization	Optimized asset utilization through real-time AR tracking and monitoring.
Cost Management	Maintenance Cost Reduction	Lower maintenance costs due to AR-driven predictive maintenance.
	Travel Cost Savings	Savings from decreased travel through AR-enabled remote support.
	Carbon Reduction	Reduction in carbon emissions from less on-site travel.
Sustainability and Governance	Transparency and Reporting	Enhanced real-time reporting and visualization of ESG data using AR tools
Innovation and Technology Adoption	AR Adoption Rate	Increased adoption of AR technology across field teams and operational units.

Field Applications and Results

This section presents four real-world field applications demonstrating the impact of AR technology in O&G operations. Each application highlights specific challenges, outcomes, and measurable improvements. These results showcase the practical benefits of AR across various operational scenarios, illustrating its potential to transform industry practices.

Field application 1: Equipment survey and troubleshooting

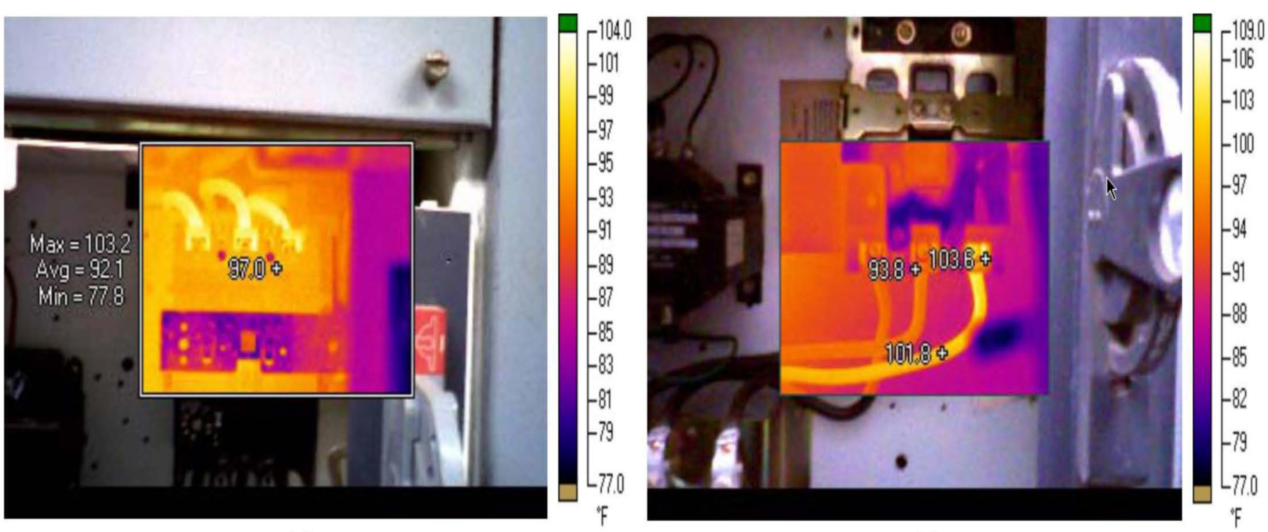
In several maintenance activities (Fig. 5a) and equipment surveys (Fig. 5b) implemented across our workshops in the eastern hemisphere, we introduced AR technology to enhance operations. The primary goal of this deployment was to enable live video communication between the local maintenance team and remote experts based in other locations. This setup allowed technicians to receive live guidance and support during troubleshooting and improve the efficiency and accuracy of operations. Technicians reported feeling more confident in their work due to the live support from remote experts, which allowed them to address complex issues more effectively without incurring additional costs. Additionally, the project enhanced the experience and skills of the local maintenance team.

(a) (b)

Figure 5—Images from the AR device camera during workshop activities: (a) a troubleshooting activity guided by remote experts, and (b) an equipment survey to help remote experts identify the tool's components

With direct access to expert guidance and the opportunity to engage in complex problem-solving in real time, technicians were able to develop their competencies and gain valuable insights from experienced professionals.

The integration of thermal lenses into AR headsets provided additional advantages in detecting electrical hot spots, identifying leaks, and diagnosing faults with greater precision see (Fig. 6a and 6b). For example, the thermal lens identified a potential issue with a water pump circuit breaker (Fig. 6b), revealing a temperature anomaly due to a loose connection, which was promptly addressed. The thermal lens technology proved essential in diagnosing faults in the transformers used in the silicon-controlled rectifier (SCR) system. While Fig. 7a shows a normal thermal image of the A-phase transformer, Fig. 7b highlights an anomaly in the B-phase transformer, where higher temperatures and hot spots indicated a fault, which was subsequently fixed by replacing the faulty transformer.



(a) (b)

Figure 6—Thermal images for water pump circuit breakers: (a) normal condition with equal temperature on A, B, and C phases; (b) loose connection as the C phase shows a higher temperature of 103.6 °F compared to the temperature of the other two phases at 93.8 °F.

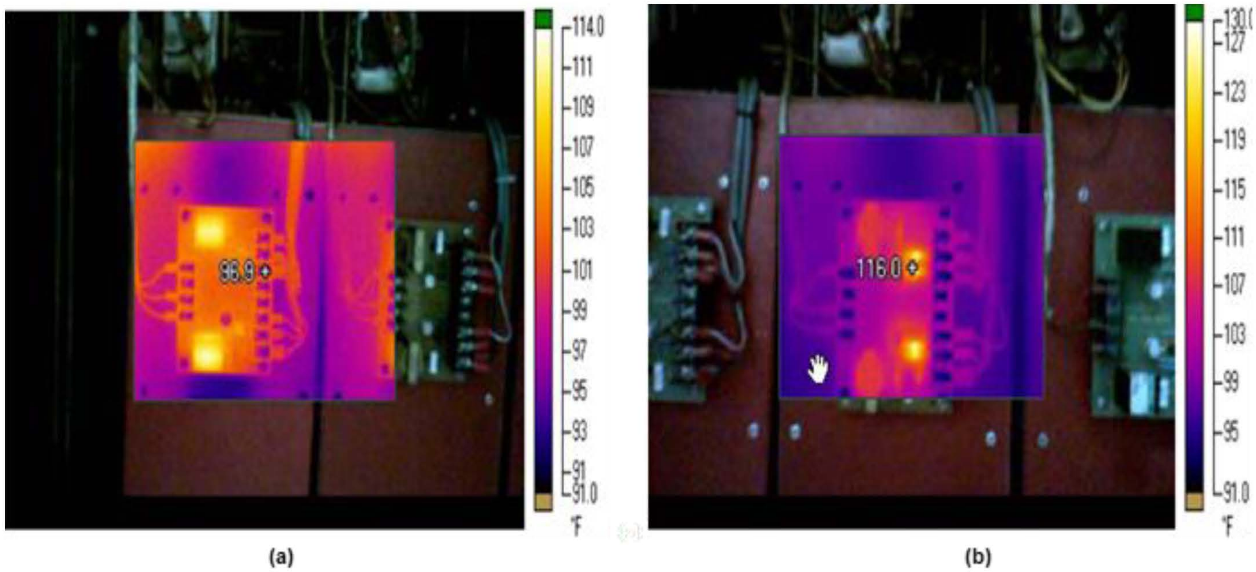


Figure 7—thermal images for transformers used in the SCR: (a) A phase fining card functions normally with two hot sports on the left side of the transformer; (b) B phase transformer has improperty fired with higher overall temperatures and a hot spot on the right side

The implementation of this technology yielded a 20%-time reduction in the maintenance job and eliminated a total of 15 days for five staff's international trips. This not only led to financial savings but also contributed to a reduction of 20 klbs (9 metric tons) of travel-related carbon emissions.

Field application 2: AR in Tubular Thread Inspection

In the second project aimed at enhancing efficiency and onsite personnel on board (POB) reduction in tubular thread inspection, we deployed AR technology within our operational framework in the eastern hemisphere. The primary objective was to confirm camera resolution and network bandwidth are sufficient for the remote inspection process of tubular threads ensuring that integrity and safety standards are consistently met.

The AR system enabled real-time video communication between on-site inspection teams and remote inspection and quality experts, providing immediate guidance during inspections. This connection allowed inspectors to perform their tasks while receiving live feedback and support, significantly improving the thoroughness and accuracy of the inspection process. High-quality 4K still photos captured for the box side (Fig. 8a) and the pin side (Fig. 8b) of the tubular during the inspections allowed remote experts to closely examine the threads and identify any visual damage. Besides the high-quality thread images, the remote experts were able to review other data from the Electro-Magnetic Interference (EMI) machine and analyze the Non-Destructive Testing (NDT) reports, ensuring a comprehensive inspection without the need to be physically present.

(a)

Figure 8—Images from the AR device camera during Tubular Inspection Activity: (a) shows the Box side, and (b) shows the Pin side, where high-resolution photos assist remote experts in identifying any visual damage.

By communicating directly with experts, technicians could more effectively identify potential issues, reducing the likelihood of oversight. Inspectors were also able to capture photos, stream videos, and receive annotations on images from the remote experts during the inspection, creating a detailed record for quality control, reporting, and future training. The implementation of AR technology in tubular thread inspections resulted in notable improvements in operational metrics (i.e. improved efficiency, reduced POB, enhanced inspection accuracy, comprehensive record-keeping, error reduction, and increased technician expertise).

Moreover, the project played an important role in increasing the expertise of the local inspection team. With direct access to remote expert guidance, technicians gained valuable insights into inspection techniques and best practices, enhancing their skills and confidence.

Field application 3: Virtual Auditing

In a series of audits conducted across our facilities in the western hemisphere, we utilized AR technology to enhance the efficiency and accuracy of compliance and safety inspections (Fig. 9). The primary objective of this AR implementation was to enable remote auditors based in the eastern hemisphere to oversee and guide the on-site team in real-time, eliminating the need for travel while maintaining rigorous audit standards.

(a) (b) (c)

Figure 9—AR headset photos for remote audit: (a) displays the equipment view, assisting in reading the calibration label; (b) shows an annotation from the remote auditor, instructing the local team to record the serial number (SN); and (c) presents the lab setup layout, allowing the auditor to verify that materials are stored and organized according to standards

The high-quality still images and recorded videos enabled auditors to check labels, documents, and tools (Fig. 9a), ensuring that even the smallest details were accurately reviewed. This capability allowed remote auditors to provide precise, immediate instructions through real-time video streaming and on-screen annotations (Fig. 9b), significantly reducing miscommunications and audit-related errors. It also enabled the remote auditor to view the shop layout (Fig. 9c) to assess whether equipment, tools, and materials are organized and stored according to compliance and safety standards. The AR deployment led to a 20% reduction in audit time. Additionally, this setup resulted in a 30% decrease in overall audit costs by minimizing the need for on-site auditor presence, resulting in savings on travel, accommodation, and downtime expenses.

On-site staff reported enhanced confidence and efficiency due to the immediate feedback and guidance provided by remote experts. This access to real-time expert input allowed personnel to address compliance issues promptly, ensuring that audit standards were met effectively. Additionally, the AR-enabled audit process contributed to environmental goals by reducing travel-related CO_2 emissions, aligning with our commitment to sustainable practices.

Filed application 4: Rig site operation

In a series of pilot projects conducted with our partner in Norway, we leveraged the AR technology to support field tests of a proprietary wired drill pipe, which provides two-way high-speed data transmission up to 200 kbps and conveys 300W power from surface to downhole. The primary goal of using AR in this context was to enable high-quality, real-time video streaming, connecting the local field team with remote experts based in other locations in both the western and eastern hemispheres. Through live video and 4K high-resolution photos captured when the tools were under test on the rig floor (Fig. 10), the Houston team was able to remotely view and analyze on-site data screens and system parameters, ensuring accurate interpretation without the need for physical presence.

(a) (b)

Figure 10—AR Photos for Pilot Project. (a) shows tools under test on the rig floor, while (b) displays project data from one of the computers inside the doghouse

The photos captured and videos recorded during the trial have become invaluable resources, as they offer a comprehensive visual record of each step and decision made on-site. This documentation will serve as a reference for replicating similar projects in other locations, enhancing consistency and accuracy in future deployments. The detailed footage will allow new teams to understand the technical requirements and best practices established in Norway, enabling smoother implementations across different sites.

This approach not only increased operational efficiency and accuracy but also cut the need for experts to travel and reduced POB and carbon emissions. Additionally, the local team gained valuable skills, fostering greater independence and confidence. By leveraging AR, we achieved the dual benefit of improved operational outcomes and enhanced skill development among field technicians, paving the way for streamlined, efficient project rollouts in the future.

What is Next

Building on the achievements of our AR-driven initiatives, future developments will emphasize the integration of digital workflow (e-checklist), thermal lens, and advanced data integration to further enhance operational efficiency. The digital workflow will automate illustrated step instructions and enable real-time completion, verification, and storage of results for each inspection job within the AR interface.

By reducing manual paperwork, this solution will improve data accuracy, speed up reporting, and enable instant data retrieval, supporting better decision-making and regulatory compliance. This integration with a thermal lens will support both preventive and predictive maintenance, as visual thermal cues in the AR interface will guide technicians in prioritizing high-risk areas.

Data Integration will unify and standardize data streams from AR technologies, internet of things (IoT) sensors, and legacy systems into a centralized analytics platform. This real-time data sharing will enable deeper analysis, trend forecasting, and automated alerts across facilities, promoting proactive resource management and more accurate risk assessment. Ultimately, these combined technologies will create a more responsive, connected, and intelligent O&G operation, aligned with our goals for efficiency, safety, and sustainability. They will reduce operational costs and adapt to industry demands for greener and more streamlined processes.

Conclusions

Our work highlights the successful integration of AR technology in the O&G industry, demonstrating its potential to improve operational efficiency and safety. By applying AR in real-world scenarios, we have observed benefits across maintenance, inspections, remote audits, and knowledge sharing.

Our field applications reveal how AR has improved communication, user experience, operational efficiency, safety, and sustainability. By utilizing advanced hardware, such as head-mounted displays, and specialized software, we integrated AR seamlessly into daily workflows, achieving improved KPIs, like reduced downtime, increased accuracy, and faster response times. Through real-time expert guidance and hands-free functionality, AR not only generated cost savings but also laid the groundwork for future applications, including advanced training and predictive maintenance.

We addressed challenges, such as hardware limitations, connectivity issues, and user training, by selecting suitable equipment, utilizing private networks and mobile hotspots, and gathering regular feedback. Insights gained from these field deployments have also enriched our training resources, empowering the local teams to proactively handle future tasks independently and enhancing overall process efficiency and reliability in the industry.

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