A REVIEW ON SUPERVISORY CONTROL AND DATA ACQUISITION (SCADA) SYSTEMS FOR FPSO UNITS

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ABSTRACT

Floating Production Storage and Offloading (FPSO) units are key assets in modern offshore oil and gas industry. FPSOs posses the ability to extract, process, store and transfer petroleum and natural gas from multiple offshore reserves. Such units bring key mobility advantage to offshore oil and natural gas production operations. Data acquisition and monitoring solutions are deployed on FPSO for operational efficiency, safety, decision making. However, traditional SCADA-based data acquisition and monitoring solutions require human interference and initiative to take action against changing operational circumstances. With recent advancements in machine learning field and its applications in data science, capabilities of data-based systems have improved significantly. In this study, current literature of SCADA-based systems are reviewed and potential affects of new approaches are presented.

Keywords: FPSO, SCADA, Real-time Monitoring, Operational Intelligence, Offshore Production
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1. INTRODUCTION

Floating Production, Storage, and Offloading (FPSO) units are gaining increasing global importance in meeting evolving energy demands due to their mobility, processing capabilities, and storage capacity. However, as operational complexity in offshore production facilities rises, these units face significant challenges in ensuring operational continuity, maintaining safety, and optimizing production in real time. Existing systems often fall short in coordinating the numerous onboard and environmental subsystems under dynamic field conditions, leading to delays and inefficiencies (Gowid, 2017; Honjo et al., 2021).

In the high-risk conditions of offshore oil operations, SCADA systems offer a potential solution to issues that cause delays and inefficiencies by enabling centralized control, automation and data visualization. In this context, SCADA technologies continue to evolve alongside digital oilfield approaches. These systems can not only be integrated into a unified monitoring and control framework but have also become essential for improving decision-making processes and reducing downtime (Carvajal et al., 2017; Allen & Smith, 2012).

By developing a consolidated framework that integrates SCADA systems with real-time operational intelligence, supported by artificial intelligence and machine learning, it will be possible to enable capabilities such as predicting failures, detecting anomalies, and optimizing performance. Such advancements offer an opportunity to transform FPSO operations from traditional supervisory models into intelligent, data-driven ecosystems, thereby fostering the creation of resilient infrastructures (Onyeke et al., 2024)

A SCADA-integrated framework specifically tailored for FPSO operations (see Figure 1) supports not only conventional process control but also real-time diagnostics, predictive fault dedection, and strategic decision support, thereby reducing production losses (Han et al., 2021). Beyond improving technical efficency, this model contributes to achieving economic and environmental goals (Onukwulu et al., 2023).

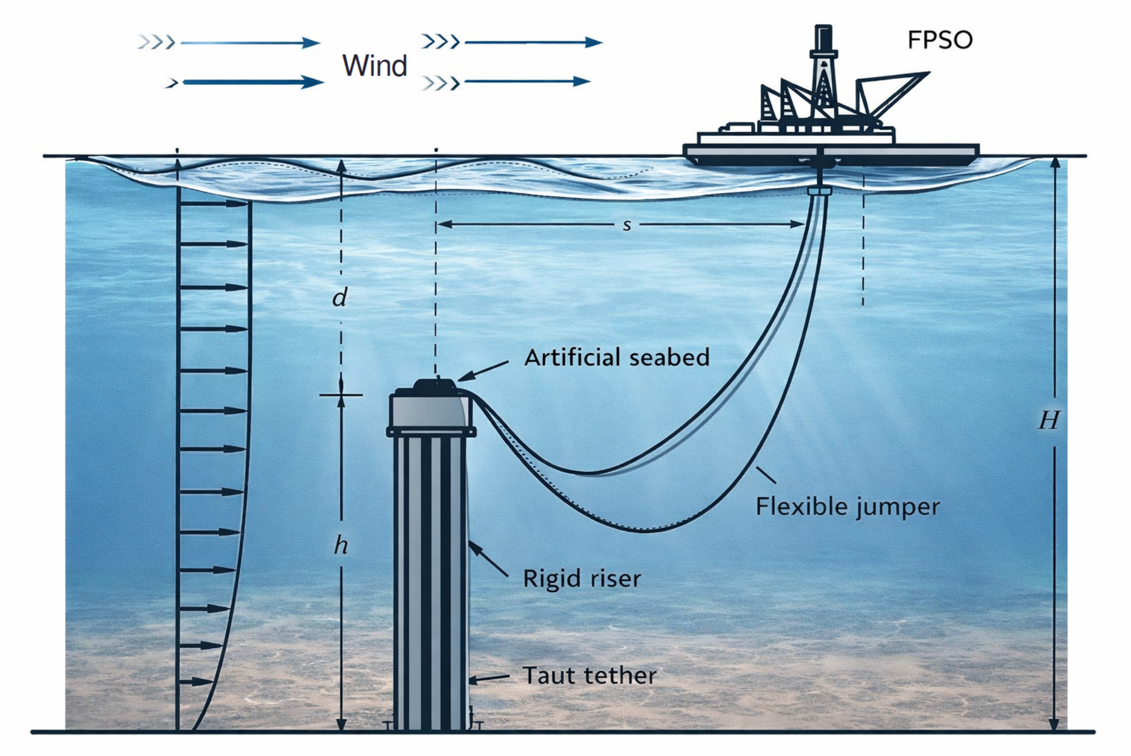

Figure 1: Arrangement of FPSO production system (Han et. All, 2021).

With a significant portion of the global FPSO fleet aging, the need for such a framework to extend asset lifecycle is growing steadily. As a result, offshore operators are increasingly open to investing in data-driven technologies that can enhance inspection routines, monitor degradation trends, and automate regulatory reporting compliance (Igbadumhe & Feijo, 2023). Through SCADA functionality, offshore operators can more accurately predict equipment failures, reduce emergency shutdowns, and better align maintenance activities with production objectives. These capabilities are particularly critical in developing markets like Turkey, where resource constraints demand lean and intelligent infrastructures. Achieving production targets without compromising safety or efficiency is vital for these markets. Moreover, the integration of SCADA into FPSO operations represents not only an engineering innovation but also a strategic transformation. This transformation defines a framework that not only digitizes data collection processes but also leverages that data for operational foresight and adaptive learning (Onaghinor et al., 2022). In the digitization of processes, the proposed SCADA-integrated model serves as a backbone that organizes production, energy management, safety assurance, and performance analytics. This SCADA-integrated model also ensures transparency, efficiency, and safety across all aspects of offshore oil and gas production from the perspective of offshore operators (Ozobu et al., 2023).

Supported by theoretical synthesis and industry expertise and drawing on case studies from oilfields within the framework of Health, Safety, and Environment (HSE), next generation SCADA systems aims to present a unified model that integrates sensor networks, communication protocols, analytics engines, and visualization dashboards into a single operational schema. It also offers a practical methodology for the implementation, performance evaluation, and adaptability of new SCADA systems across various offshore environments (Igbadumhe & Feijo, 2023)

2. Literature Review

In offshore oil and gas production, especially within FPSO environments, SCADA-based monitoring and control systems present significant opportunities. The increasing complexity of offshore operations and the growing need for intelligent automation have substantially driven research into integrated control systems such as SCADA. The work of Carvajal et al. (2017) laid a foundational basis in this field by conceptualizing intelligent digital oilfields.

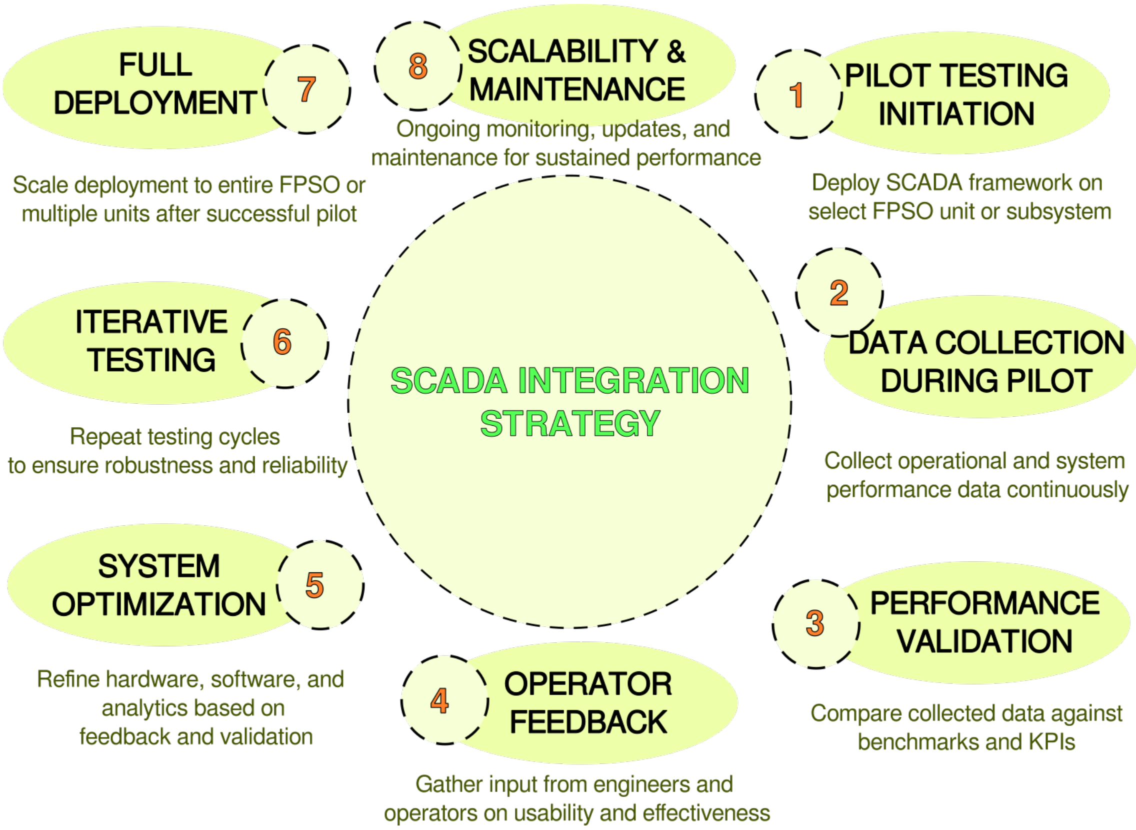

Figure 2 : Integrated SCADA systems flow diagrams.

The integration of operational intelligence into SCADA systems transforms them from mere data acquisition tools into platforms for decision support and performance optimization (see Figure 2). Allen and Smith (2012), through their examination of "intelligent completion systems" emphasized that SCADA can evolve into a predictive system. Similarly, the Real-Time Production Operation (RTPO) system developed by Dutra et al. (2010) demonstrated that SCADA is a system based on adaptive learning and optimization driven by continuous feedback. These perspectives define a paradigm shift, particularly within offshore environments.

Technological advancements such as artificial intelligence (AI) and machine learning (ML) algorithms have further enhanced SCADA functionality in FPSOs. Bello et al. (2015) explored AI applications in drilling and production, noting that integrating SCADA systems with ML models improves reliability and predictive capabilities. Onyeke et al. (2024) showed that the integration of predictive analytics into industrial control systems significantly enhances fault detection accuracy and minimizes maintenance delays. These findings underscore the necessity of incorporating such technologies into the future evolution of SCADA systems.

FPSO units typically contain equipment from various manufacturers, each operating with their own proprietary control systems and data protocols (see Figure 3). Such disconnected systems have been observed to be both inefficient and vulnerable to attack (Aminu et al., 2024). Without interoperability and integration strategies, SCADA systems remain isolated and limited in their capabilities. Therefore, it has been emphasized that a SCADA-integrated framework must ensure encrypted, authenticated, and monitored communication channels throughout the production network.

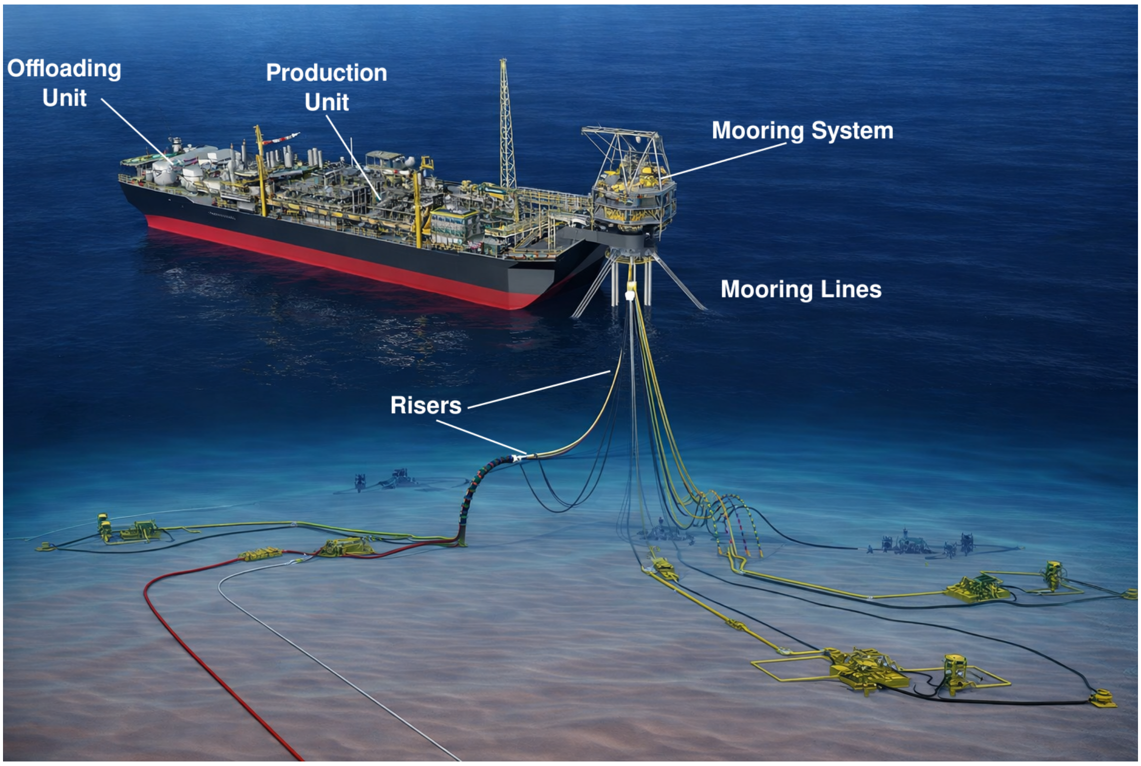

Figure 3: Sample arrangement of FPSO and production well

Hwang et al. (2018) advocated the importance of SCADA integration in condition-based maintenance systems for LNG FPSOs to enable timely detection of abnormal operating conditions. Adewoyin (2022), on the other hand, emphasized that risk-based inspection frameworks could significantly benefit from SCADA-generated data, especially when monitoring aging infrastructure (see Figure 4). He suggested that early detection of corrosion, fatigue, and pressure anomalies through such integration could help extend asset life.

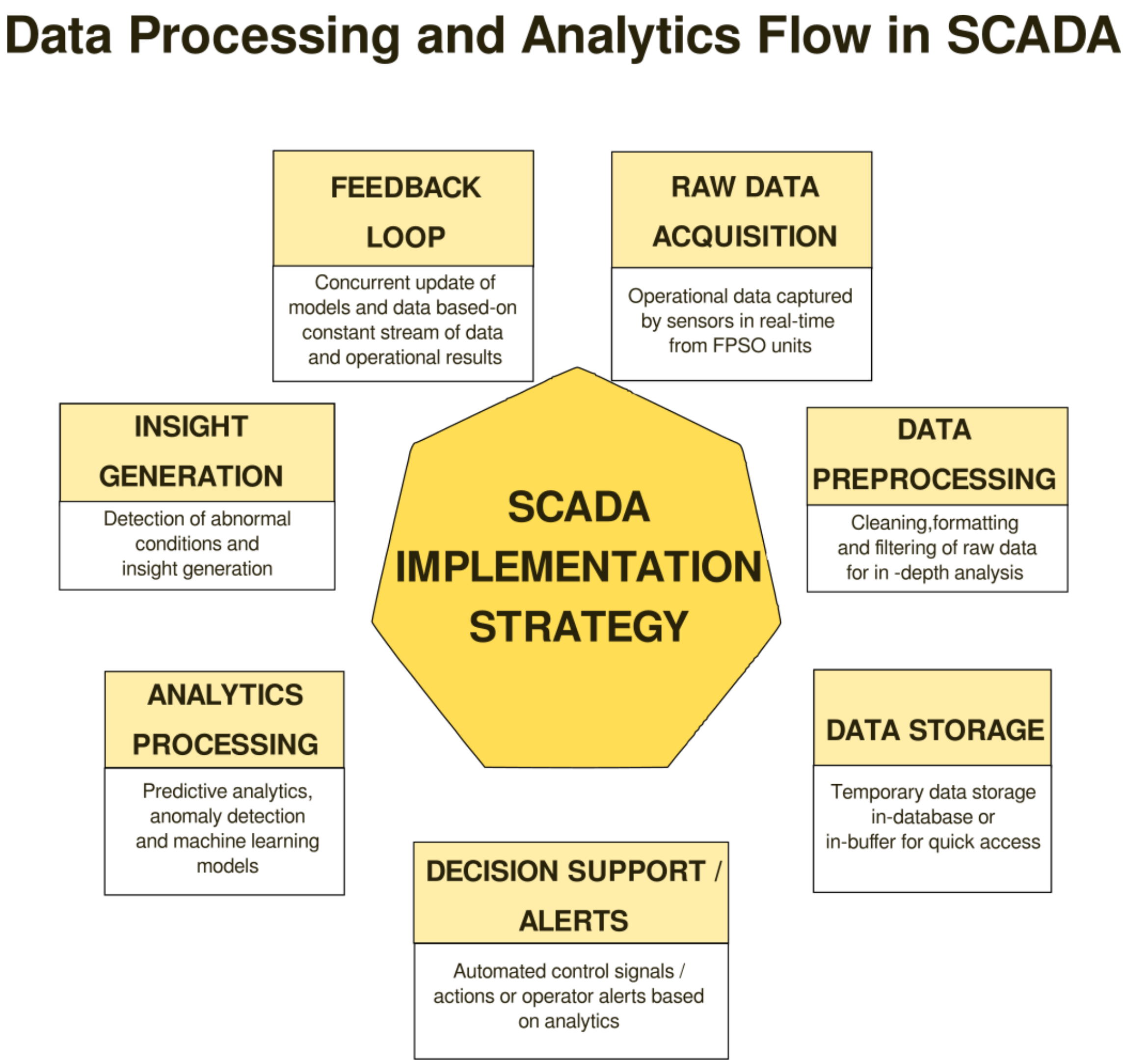

Figure 4: SCADA data processing and analytics flow diagram.

From a process excellence perspective, Esan et al. (2023) examined the integration of Lean Six Sigma and Robotic Process Automation (RPA) with SCADA dashboards to automate quality assurance and reduce human error. This integration is critically important on FPSOs, where the balance between remote operation and automation is delicate, as human oversight must be supported by clear and reliable system feedback (see Figure 4).

Offshore systems are generally vulnerable to cyber threats. Ilori et al. (2022) emphasized the importance of SCADA systems from a cybersecurity perspective and highlighted the necessity of integrating threat detection, access controls, and anomaly filters directly into SCADA platforms. They stated that this would help protect against unauthorized access, signal spoofing, or data corruption.

Adewoyin (2021) and Dienagha et al. (2021) highlight that SCADA-integrated systems can play a significant role in global carbon reduction efforts in the oil and gas sector by optimizing combustion control and reducing fugitive emissions. Studies by Ezeanochie et al. (2022) and

Egbuhuzor et al. (2023) have examined workforce enablement and human-machine interaction, emphasizing that automation frameworks must also consider operator feedback, training, and decision authority. Such user-centric designs are becoming increasingly important for FPSOs, where complex systems must be managed in isolated and high-stress conditions. The literature reveals a need for a synthesized model that integrates all relevant subsystems into a unified framework for real-time monitoring and operational intelligence on FPSO units. This study focuses on a model with self-learning capabilities, multi-platform interoperability, and intelligent decision support, thereby presenting a methodology that designs a modular, scalable, and future-ready framework.

The ability of SCADA systems to automatically record operational parameters, flag deviations, and maintain auditable records makes them valuable tools for supporting environmental, health, and safety compliance requirements beyond mere technological integration and system-level design. This capability contributes to mitigating reputational and regulatory risks in FPSO operations.

The predictive dimension of SCADA is critically important for monitoring flaring, leak detection, and process irregularities that contribute to greenhouse gas emissions. Han et al. (2021) noted that the use of SCADA-linked dynamic prediction models, when integrated into broader ESG (Environmental, Social, and Governance) reporting ecosystems, can enable FPSO operators to automate sustainability reporting, enhance audit readiness, and align with voluntary standards such as the Global Reporting Initiative (GRI) or ISO 14001 protocols.

In FPSO operations, where operators are often required to respond to alarms or adjust system parameters without immediate technical support, the potential of SCADA to optimize human-machine collaboration in offshore environments is highlighted in relevant studies. Research on human-machine interaction emphasizes that dashboards should incorporate layered visualization, color-coded risk prioritization, and context-aware notifications to enhance safety and decision quality (Omisola et al., 2023; Ozobu et al., 2023).

Kanu et al. (2022) state that agile project execution frameworks in the energy sector can benefit from SCADA-derived data by supporting scope adjustments, cost control, and performance metrics in capital-intensive offshore projects. Uzozie et al. (2022) demonstrate that cross-continental supply chain operations can utilize SCADA-integrated logistics dashboards to reduce downtime, optimize resupply schedules, and provide early warnings for equipment failures that may disrupt project workflows. These findings highlight that SCADA platforms, beyond real-time control, can also serve as critical enablers in areas such as strategic decision-making, capital planning, and enterprise performance management within the broader context of economic resilience and macro-scale project execution.

The literature also emphasizes that FPSO systems must be adaptable to emerging innovations such as edge computing, blockchain integration, and AI-driven fault diagnostics. Ogunwole et al. (2022) and Ojika et al. (2023) argue that SCADA platforms should serve as hubs for new technologies, requiring forward-compatible system architectures. This future readiness is critically important to ensure that FPSO assets remain competitive in a market characterized by rapid digital transformation, evolving regulatory environments, and increasing environmental scrutiny.

In conclusion, the literature reflects a rich mosaic of innovations, challenges, and strategic priorities that support the necessity of a SCADA-integrated framework in FPSO operations. Although the scope varies from maintenance optimization to sustainability and cybersecurity, the studies converge on a common idea: real-time visibility, predictive intelligence, and operational coordination are no longer luxuries but necessities in modern offshore production. However, despite this consensus, there remains a lack of a fully defined and deployable framework that can translate these diverse needs into a coherent operational plan. The methodology presented in the next section aims to fill this gap by grounding its design in these insights and offering a forward-looking roadmap for a SCADA-enabled, intelligent, and resilient FPSO infrastructure.

3. Next Generation SCADA infrastructure for FPSOs

One-generation older systems utilized a limited number of sensors paired with rudimentary server systems to store data pushed from edge devices. These servers often ran Statistical Process Control (SPC) algorithms for data analysis (Olayinka, 2022). Results were sent to dashboards, which were then monitored by human operators to take necessary actions (See Figure 5).

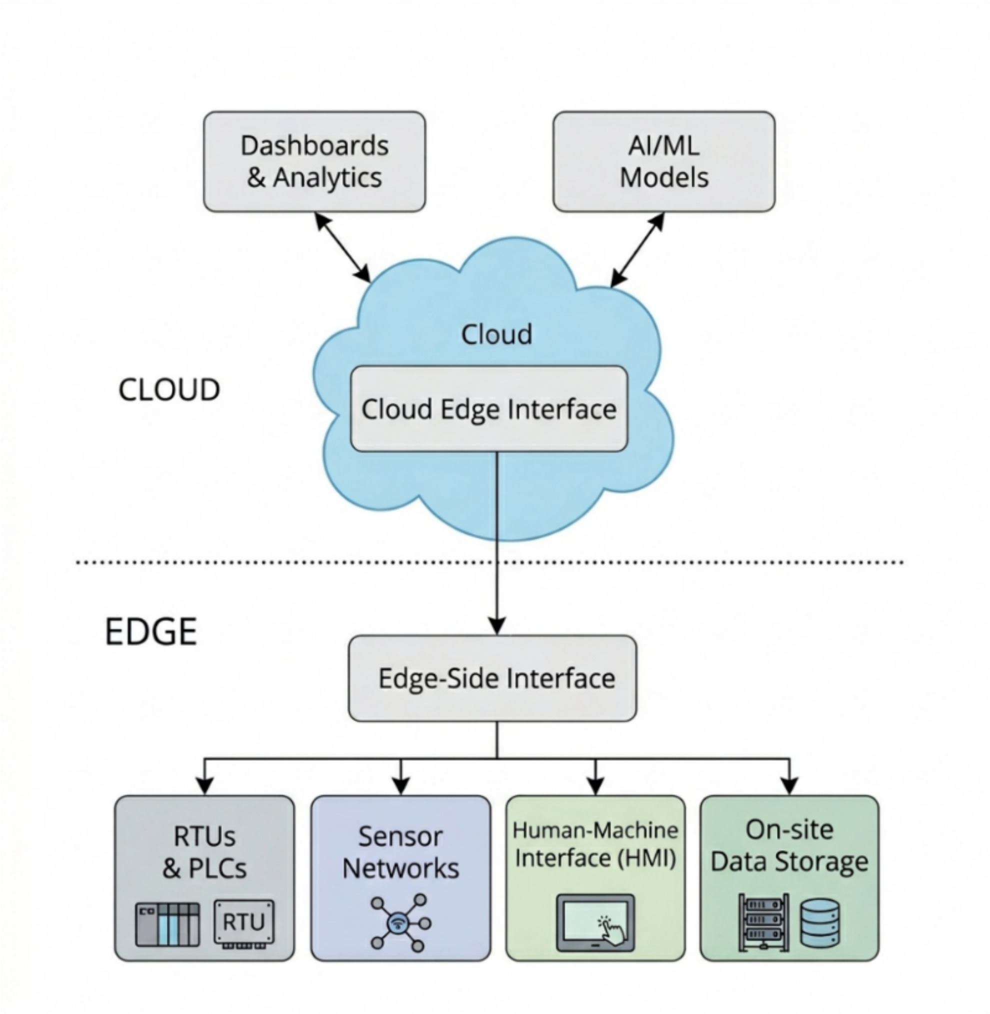

Figure 5: Old type SCADA system architecture

Current systems utilize a standard Cloud/Edge architecture, with field operations guided by established Supervisory Control and Data Acquisition (SCADA) and Programmable Logic Controller (PLC) principles. Edge devices, comprising SCADA systems and PLCs, acquire data from field sensors and store it locally. On a pre-determined cycle, these devices transmit real-time and stored data to the cloud through vendor-specific interfaces for centralized processing. In the cloud, comprehensive analysis is performed using machine learning, deterministic models, or a hybrid of both. Based on this analysis, a control algorithm would determine the long-term action policy. This decided action policy was then sent back through the cloud gateway to the edge devices. Any time-critical action is executed on-site by edge devices to avoid latency. Human operators provided continuous high-level supervision of the entire process via Remote Terminal Units (RTUs). Clearly, in each subsequent step in its evolution, SCADA-based systems gained new capabilities.

Next generation SCADA-based systems represent a significant shift from their legacy counterparts in their design: modularity, scalability and event-driven architecture is prioritized. This is a progression from old architectures plagued with rigidity, latency and integration issues. Modern architecture puts significant emphasis on distributed, intelligent and autonomous operations across various operation conditions (see Figure 6).

Modularity seeks to break every individual function of the system into replaceable, independent components or services. Each "module" can be maintained, operated or scaled independently. This granularity brings in upgradability, problem isolation in case of faults and flexibility in system customization regardless of other components (Abdulsalam et all. 2020). Keeping the system architecture modular often need clearly defined and easy-to-work interfaces. Adoption of open standards and open protocols such as OPC UA, DDS and RESTful APIs enables compatibility across various hardware and software modules such as IIoT (Industrial Internet of Things) sensors from different vendors or external microservices. Microservices are an architecture concept where a single application is composed of many small, loosely coupled, and independently deployable services. Microservices keep the system modular and resilient. If needed, external web-based microservices can also be incorporated to increase system resiliency, flexibility and to cut down computation costs.

Scalability is defined as the capacity of a system to accommodate increasing workloads or expanded functional requirements without a proportional loss in performance or the need for a structural redesign. Modern systems need to respond to increasing compute loads in an efficient manner. By taking advantage of container-based architecture and using technologies like Docker and Kubernetes, system computational resources can be expanded as more data streaming devices added to the system (Vijayakumaran et all. 2020). Container-based services encapsulate necessary software and allocated hardware resources. Operations that need more compute in certain time periods can benefit from real-time scaling of compute by leveraging microservices in addition to containers. While microservices provide modularity, they also facilitate horizontal scalability by allowing specific services to scale independently under heavy loads. The ability to support extensive sensor networks and distributed stations is critical for maintaining low-latency operations and preventing the exhaustion of centralized computational resources.

Event-driven architecture is characterized by use of "events", which are significant changes in state or certain occurences like: a sensor reaching a pressure threshold or a user clicking a button. In this architecture, data sinks and reservoirs do not poll data constantly or in fixed scheduling intervals. Instead, they publish data when an "event" takes place and subscribing devices respond accordingly. By limiting the communication only when necessary, resources are utilized more efficiently and faster response times are achieved (Abbas et all. 2014). An event streaming framework like Apache Kafka and a data broker like MQTT exemplify event-driven concepts.

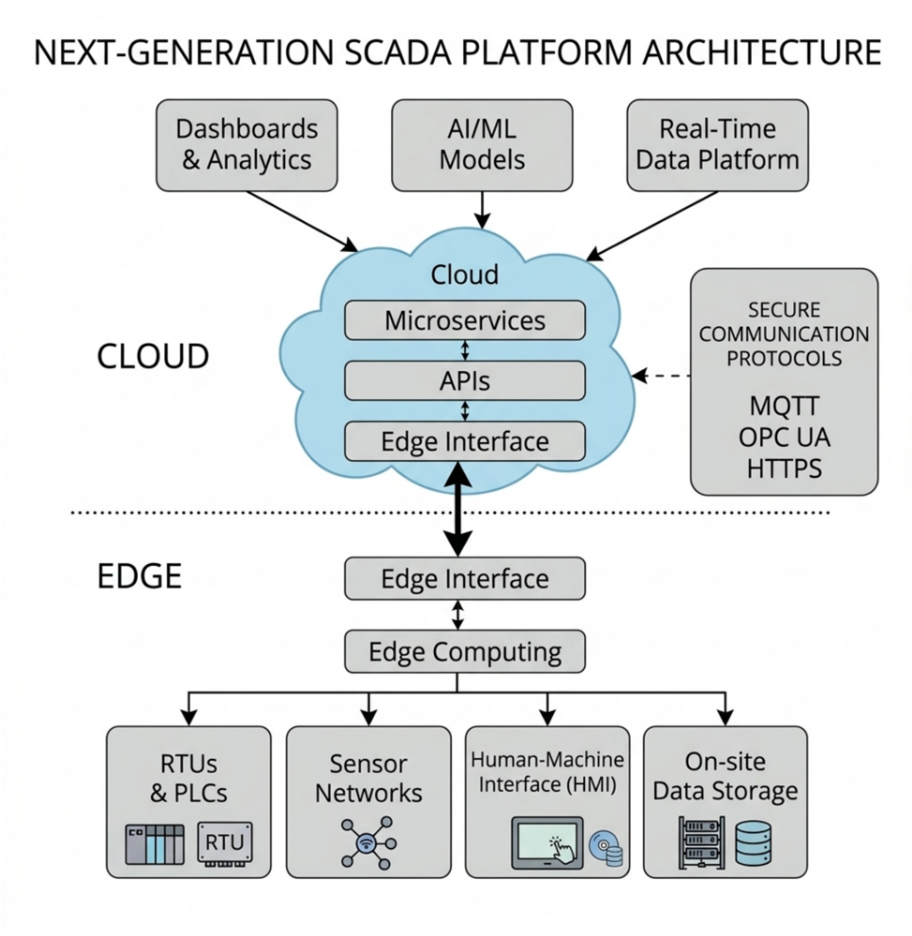

Figure 6: Next Generation SCADA system architecture

Legacy data systems often utilized statistical process control algorithms in decision making processes. With advancements in machine learning based methods, more precise predictions and faster responses to changing conditions are possible. Predictive maintenance cuts down downtime and further maintenance costs. Faster decision making enables faster responses to undesired incidents, increasing operational safety and resiliency.

This proposed next-generation system architecture transforms SCADA systems into an interconnected operational intelligence platform by harmonizing real-time field data, AI-driven insights, and enterprise-level business metrics. It provides a centralized interface where technical teams can monitor telemetry and AI diagnostics alongside integrated security and performance management tools. Modularity of the architecture provides interoperability, ensuring future-proofing against digital demands of tomorrow.

4. Conclusions and Future Work

The integration of Supervisory Control and Data Acquisition (SCADA) systems within Floating Production Storage and Offloading (FPSO) units presents a transformative approach to real-time production monitoring and operational intelligence. This literature study has developed a comprehensive framework that combines advanced sensor configurations, robust data acquisition pathways, secure communication protocols, advanced data analytics, and intuitive visualization tools tailored for the complex offshore environment.

As literature shows, applications and implementation of SCADA-based systems in FPSO's are mostly aligned with non-offshore applications. Many maritime and offshore filed-specific problems can possibly be solved from data-driven approach that said systems offer. Real-time monitoring combined with real-time feedback capability can lead to unexplored approaches in mentioned problem fields (Han et. all 2021). Future applications of SCADA-based systems on specific problems like: ship motion analysis, ship stability analysis, dynamic positioning, FPSO offloading-systems, mooring and riser analysis and structural-health monitoring are subject to further studies and likely problem subjects that can leverage data-based real-time solutions.

Continuous advancements in autonomous technologies and robotics offer further opportunities to enhance last-mile operational control and maintenance tasks within FPSO units (Uzozie et al., 2022; Ubamadu et al., 2022). These developments call for interdisciplinary collaborations combining control engineering, data science, cybersecurity, and environmental science to foster holistic solutions addressing the multifaceted challenges of offshore production systems. By addressing current limitations and exploring future technological integrations, this framework is positioned to adapt to the dynamic environment of offshore oil and gas production, promoting innovation and resilience in this critical industry sector.

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