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The Role of Remote Operated Vehicles (ROVs) in Offshore Renewable and Oil & Gas Asset Integrity

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Abstract
The increasing sophistication of offshore projects within the realms of renewable energy, as well as the oil and gas industry, makes the need for effective asset integrity management even more crucial. In these challenging working environments, ROVs, or remotely operated vehicles, have become indispensable for inspecting, maintaining, and monitoring these marine environments. This focuses on the evolution of ROV technology and its applications in inspection, digital asset management, and offshore integrity, to which ROVs are omnipresent. ROVs visually and photogrammetrically inspect the offshore wind turbine foundation and measure the ultrasonic thickness of pipes, and also survey cathodic protection on subsea pipelines and risers. This means they work under specially controlled environments and attend to tasks that are better achieved without the use of Deep-Sea Divers. This proves rational as ROVs reduce operational risks and work more efficiently in high-risk, Deepwater conditions. There are supporting systems and software that inspect and optimize data, and these ROVs work best when combined with the data engineering platforms as FDVR, COABIS, and SENSE. ROVs can use the data to create insights, and have history comparison, anomaly detection, compliance, and digital twin capabilities for predictive maintenance. The incorporation of ROV inspection custom technologies into such platforms improves decision-making and complements ROV risk-based inspection strategies. ROVs' operational issues, such as weather dependency, excessive amounts of data, and sensor integration problems, continue to streamline ROVs through increased autonomy, sensor fusion, and Artificial Intelligence recognition of defects. As the scale and complexity of the offshore energy systems continue to grow, the ROVs will be critical in maintaining structural safety, compliance with regulations, and sustainability. ROVs will also be critical in the integration of digital tools for the inspection and management of offshore assets, giving ROVs the primary position in the management of offshore assets and integrity.

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1. Introduction

The framework of energy security, sustainability, and economic development for countries around the globe and the developing offshore energy infrastructure is diplomatic fuel on an international scale. Oil and gas demand is on the rise and continues to expand, especially in developing economies where offshore energy reserves are a significant share of national energy supply (Canbaz *et al*, 2021; Legorburu *et al*, 2022). Global investments in offshore renewable energy, particularly in offshore wind farms, signify an intention to pursue international targets for decarbonization and energy source diversification (Guo *et al*, 2023;

Lei *et al*, 2023). Both oil, gas, and renewable energy offshore sectors demand complex, intensive, and expansive subsea and sea surface infrastructure, including pipelines, risers, turbines, foundations, and extensive cabling networks that are positioned and operated in some of the most demanding environmental conditions on the planet (Cui *et al*., 2022; Rodríguez *et al*., 2023). The design and operation of these facilities, beyond optimizing for efficiency, durability, and resilience, must also incorporate active asset management and capital asset management techniques (Yakoot *et al*., 2021; Omrany *et al*., 2023).
The reliability and use of offshore structures are more complicated than onshore systems. "Offshore structures, such as wind turbines, have complex structural and geotechnical components" (Amiri *et al*., 2021; Leng *et al*., 2023). These above-water structural systems are exposed to hydrodynamic maritime forces, salinity, varying water temperatures, and depth, which leads to corrosion, fatigue, and biological fouling. If not monitored, offshore structures could deteriorate and lose operational functionality, which increases catastrophic risk (Clarkson and Williams, 2021; Sabouni, 2023). These structural and geotechnical systems not only deteriorate over time, but also cause major financial loss, severe human safety and environmental hazards, and increased regulatory scrutiny. Therefore, as highlighted in recent research, securing asset integrity became one of the offshore risk control systems (Adebisi *et al*., 2021; Prodhan *et al*., 2022).
Remote Operated Vehicles (ROVs) are integral to remote offshore integrity management (Dalhatu *et al*., 2023; Gower, 2023). ROVs are considerably more efficient, safer, and cost-effective than traditional vessel inspections performed by divers, which involve significant safety concerns and may be restricted by depth, accessibility, and adverse environmental conditions (Lorenčič, 2022; Tait *et al*., 2023). Operating ROVs equipped with still and video cameras, sonar systems, and various NDT tools, operators can gather real-time, intricate structural data (Venkatesh *et al*., 2022; Rizzo, 2022). With the ability to identify and document defects more easily, the use of remotely operated vehicles decreases expensive manned undertakings that are fraught with danger (Shafi *et al*., 2023; Quamar *et al*., 2023).
Using ROVs, as every other business is working to integrate automation and digitization, is set to revolutionize (Johansson *et al*, 2021; Stein, 2023). Moving away from ROV data, ROV's integration to sophisticated asset management systems such as digital twins and predictive maintenance frameworks allows operation from a purely reactive to predictive risk-based maintenance. ROVs are also effective in fulfilling the sustainability goals of the oil and gas industry as well as the renewable energy sector by reducing facility service life and lessening environmental impact (Massari *et al*, 2023; Bravo *et al*, 2023).
As more offshore projects are conducted in deep and rough waters, the need for ROVs will only increase (Massari *et al*, 2023; Agarwala, 2023). The combination of advanced ROV technology and other sustained ROV developments in autonomy, AI as well as sensor technology makes ROVs a key player in offshore asset integrity management (Bathla *et al*, 2021; Macaulay and Shafiee, 2021). The rest of this chapter addresses this issue, documenting the ROV-based inspection systems, data capturing technology, and the supporting software used to ensure structural resilience of offshore renewable and oil and gas ROV deep ocean maintenance.

2. Methodology

The function of Remote Operated Vehicles (ROVs) in offshore renewable energy and oil and gas asset integrity was thoroughly reviewed using the PRISMA approach. In addition to documents from regulatory bodies, classification societies, and professional industry associations, a systematic search was carried out across scientific databases, technical repositories, and industry publications such as Scopus, Web of Science, IEEE Xplore, ScienceDirect, and proceedings from offshore engineering conferences. To guarantee thorough coverage of academic and industry viewpoints, a well-thought-out search strategy integrated terms like "ROVs," "asset integrity," "offshore renewable energy," "oil and gas infrastructure," "inspection technologies," and "subsea maintenance."
Before filtering, duplicate entries were eliminated, and all retrieved articles were put into a reference management platform. Studies addressing ROV applications in the inspection, monitoring, maintenance, or repair of offshore energy assets were included in the eligibility criteria. Articles that only discussed autonomous underwater vehicles (ROVs) or had no connection to offshore renewable energy or oil and gas activities were not included. Titles and abstracts were used for the first screening, and full-text evaluation of possibly pertinent sources was done to make sure they matched the review's goals.
Information regarding ROV operational roles, technological capabilities, digital technology integration, safety or regulatory frameworks, and comparative performance across various offshore sectors was the main topic of data extraction. High-caliber industry reports and peer-reviewed research were evaluated for methodological soundness and contribute to the understanding of how ROVs improve asset integrity management. Bias risk was assessed, especially for materials produced by the industry, where reporting may be influenced by economic interests.
The synthesis of findings was conducted using narrative and comparative approaches to highlight key patterns in how ROVs support offshore infrastructure. Themes identified included inspection efficiency, cost-effectiveness compared to traditional diver-based methods, safety improvements, technological innovations such as AI integration, and cross-sector lessons transferable between oil and gas and renewable energy domains. This systematic methodology established a comprehensive evidence base to evaluate the evolving role of ROVs in strengthening offshore asset integrity and informing future technological, regulatory, and operational strategies.

2.1. ROVs in Offshore Operations

Advancements in remotely operated Vehicles (ROVs) have greatly improved the techniques used for inspection, monitoring, and maintenance in offshore environments. Due to the growth of the offshore energy sector, which combines traditional oil and gas production and continuing development in renewable energy, the importance of safe and efficient subsea operations has ballooned. ROVs provide critical assistance for this transition. In comparison to traditional diver operations, ROVs provide greater levels of safety, greater operating depth, increased precision, and lower operational costs (Starko *et al*., 2022; Duan *et al*., 2023).
Remotely operated vehicles (ROVs) are classified according

to the tasks they perform, their payload, and the power they require. ROVs tethered, unmanned bodied, and controlled underwater robots equipped with lights and cameras, with a surface or offshore platform vessel. They perform multiple underwater tasks and feature manipulator arms and sophisticated sensors.

Observation Class ROVs are intended for light optical inspection surveys, which require contact with the target structure. They include basic camera and sonar equipment as well as basic light and thermal sensors. Low operational costs and small sizes make them portable, which is appropriate for offshore inspections for wind turbine foundations and shallow water pipelines. Work-class ROVs are larger than the previous type and even more powerful. They can go to greater depths and perform more complex operations. These ROVs include heavy-duty manipulators, cutters, and tested NDT equipment. They can serve to help with construction and maintenance, as well as perform detailed integrity assessments in the oil and gas fields. Hybrid ROVs, as the name suggests, are in between the two previous types and can perform light inspections and intervention. More advanced units can even operate with autonomous navigation, having the tethered control of an ROV while also functioning as a UAV.

This is useful for the operators as they can select the most appropriate ROV. The balance between cost, capability, and environmental conditions must be met for the ROV to be optimally effective. In the past, the primary method of inspection had been using divers, which proved to be the most effective ever since diving operations began. Despite this, the practice was methodical and more of a checklist to tackle, without true out-of-the-box thinking. While conducting the operations in water, the depth of the water acts as the most difficult ‘hurdle’ to overcome. As divers go deeper, the chances of decompression sickness and nitrogen narcosis increase to dangerously high levels, not to mention the ‘buoyancy’ effects that could completely be detrimental to a person’s body (Bennett and Cibis, 2022). On top of that, diver safety is vastly compromised due to adverse factors, such as heavy rainfall and strong winds, leading to hypothermia and ice-cold water, which can lead to temperature exhaustion and hypothermia, which is a killer phase of a detrimental injury.

ROVs tackle all of the divers’ challenges head-on. These different challenges, such as the diver not having to come in contact with the highly dangerous, water-carrier exotic encroaching, and losing the contradiction tracks. Unlike the former, the new model has the capacity to go more than 3,000m deep in water. The diver is to be supported with a new technology that enhances the duration or ‘endurance’ of a diver. This not only increases the operational levels, but also the ability to take highly sensitive images or install high rigor sensors. Not to mention, there are decreasing operational costs ROVs bring in stub feet. This is due to there not being a need to find large dive support and decompression facilities (Liang *et al*., 2021; Junior *et al*., 2023). The combination of safety, ROVs being highly efficient, as well as versatile and adaptable, makes them a great and robust device for offshore management.

The demand for subsea inspection and monitoring for the wind farms is rapidly increasing. Offshore renewable energies have recently introduced wind turbine foundations for the monopile, the jacket, and the floating structure, which are subject to cyclic loading, corrosion, biotic fouling, and other complications. The deployed ROVs foundation inspection surveys the structures by employing high-resolution photographs, sonar scans, and ultrasonic gauging to identify structural decay (Lazakis *et al*, 2022; Hariharan, 2023).

ROVs are also the most important part for subsea power cables inspection and maintenance. These cables run from the turbines to the offshore substations and further connect to the land grid. They are, however, prone to burial shifts, crushing, thermal, and frictional damage. ROVs integrate highly specialized Observation class, which are cable tracking and are able to study the gradients of burial, defining the free spanning monitor of cable along with assisting in borrow protection and remedial lengthy processes. Without them, the offshore renewable energy cables would lack the strength and reliability needed for the subsea structure.

ROVs have also been deployed for seaward environmental protective monitoring of wind farms. They assess seascape bottom conditions, scour protective devices, and marine organism diversity, and help monitor regulatory and environmental compliance.

ROVs have been part of the oil and gas industry for many years, aiding in exploration, production, and decommissioning. Subsea pipeline routine inspection is one of their primary functions. ROVs equipped with cameras, sonar, and corrosion mapping tools can find coating disbandment, metal loss, free spans, and others. In the deep water, where manual inspection is impossible, ROVs may be the only acceptable method for pipeline integrity assessment. Riser inspection is another important use. ROVs equipped with ultrasonic and eddy current sensors evaluate the wall thickness, integrity of the welds, and fatigue hot spots of the risers, which connect the underwater pipelines to surface platforms. ROVs enable operators to carry out preventive maintenance essentially in the absence of failure (Allahveranov, 2021; Islam *et al*., 2022).

ROVs can also perform intervention and inspection of subsurface valves and manifolds, as well as wellheads. Work-class ROVs can and have the capacity to manipulate valves and change components, as well as aid in sudden response tasks. For intricate repairs as well as constructions that are underwater, the robust manipulators enable the ROVs to be equipped with the suitable tools.

In addition to inspection, ROVs are being woven into workflows more than before. ROV data can be uploaded to digital asset management systems, which use AI and advanced analytics for asset optimization. This helps mitigate the shift from scheduled maintenance to more proactive and predictive maintenance. This fulfills the growing need of the industry to enhance and improve the predictive maintenance for safety and cost efficiency’s reliability.

ROVs are invaluable for offshore operations where robust inspection and maintenance capabilities are required across the renewables and oil and gas and oil and gas industries. Their separation into observation, work, and hybrid classes provides ROVs with the flexibility to respond to different operational requirements. More so, as with many ROV operations, diver operations' safety and efficiency may be compromised; ROVs provide invaluable life support for operators. An illustrative case is the inspection of wind turbine foundations and subsea cables, pipelines, and risers, where ROVs obtain and provide essential data towards asset integrity and operational resilience support (Sharp and Ersdal, 2021; Wang *et al*., 2023). ROV reliance will continue growing as offshore projects go deeper and into more hostile terrains. This will be fueled by the increasing autonomy, sensor, and digital integration of ROVs.

2.2. Comprehensive Review of ROV-Based Inspection Technologies

In the offshore energy industry, ROVs have developed advanced capabilities, contributing to the complete inspection, monitoring, and maintenance of infrastructures related to renewable energy, as well as oil and gas. With the growing age of subsea assets combined with the deteriorating environmental circumstances, there is an increasingly growing need for reliable as well as unobtrusive inspection technologies withstanding high-resolution images as shown in figure 1. ROVs, and their datasets, help operators to assess the structural integrity of an object, devise a risk management strategy, and determine the possible future risk corrective measures, all without endangering their personal safety. This also describes the ROV inspection technologies, including but not limited to, visual and optical methodologies, ultrasonic testing, cathodic protection survey, laser and sonar mapping, eddy current and magnetic flux leakage techniques, as well as protected UT

The use of remote-operated vehicles (ROVs) for visual inspections is fundamental but not basic ROV-based technology since they make use of HD cameras, low-light cameras, and other lighting technology to capture images of subsea structures. ROV HD cameras allow for the assessment of the condition of the structures and growth of the living organisms attached to the platforms through visual exams of the welds and joints, and coatings. Attention to the photogrammetry technique shows it was used in improving visual inspections for subsea photogrammetry construction through the overlapping images. Employing the photogrammetry and the structure-from-motion (SfM) technique, detailed three-dimensional (3D) models of the subsea structures, like wind turbine foundations, risers, and pipelines, can be developed within a short period. This technique helps with the documentation of the structures' baseline conditions and with the detection of changes during inspections. ROVs, unlike divers, can carry more tools and work at greater depths and distances for more prolonged periods, dramatically improving the safety, cost, and effectiveness of inspections.

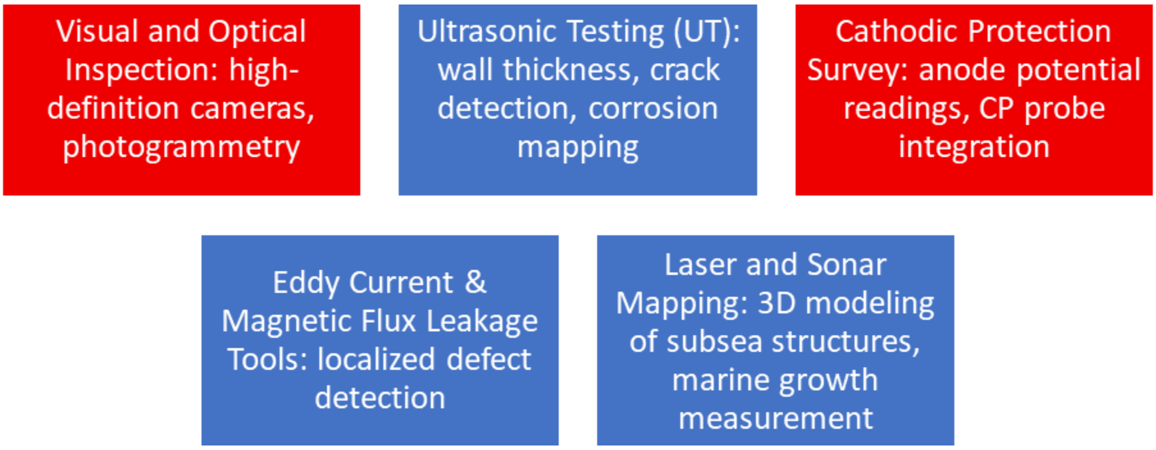


Fig 1: Comprehensive Review of ROV-Based Inspection Technologies

The merging of ROV technology with UT sensors, ultrasonic testing (UT), yields powerful non-destructive testing (NDT) methods that assist in quantifying structural integrity. UT sensors send ultrasonic high-frequency (HF) sound waves in solid metals and listen for reflected signals. The sensors then calculate the distance using the speed of sound in the measured material and the time of the round-trip of the sound. Any discrepancies in the measured (or assumed) thickness of the walls (could be multi-layer) of the solid, such as cracks or voids, as well as differing sonic velocities in metals, or partial or complete corrosion shutoff zones, cause echoes that the UT sensors analyze and sketch as corrosion maps, cracking and corrosion distribution diagrams, or walls' volumetric and area defect (crack) diagrams. The UT probes that are deployed by ROVs are mainly outfitted with manipulators or magnetic crawlers that assist in deadweight, like a submarine, and lock on with great precision to ROV manipulators to subsea structures such as pipelines, pressure vessels, or jacket structures. The further development of phased array ultrasonic testing (PAUT) allows for multi-angle in sonification, which improves the clarification of the anatomy of defects in complex geometries. Combining ROV technologies with ultrasonic probes allows for autonomous, high-precision corrosion mapping, which quantitatively evaluates the distribution of corrosion and allows for effective maintenance and assessment planning. ROVs can operate in much greater depths and more dangerous conditions than human divers can conquer; as such, ROVs have greater precision for more complex operations at such depths.

Cathodic protection (CP) is one of the essential techniques in preventing corrosion on steel structures in marine environments. In Liu *et al*. (2021) and Abusleme *et al*. (2021), it was noted that ROVs with CP probes are used to conduct in-situ measurement of the effectiveness of cathodic protection on water structures by verifying the anode potentials and structure-to-seawater potentials. These probes are classified into either contact probes that touch the structure or proximity probes that assess the potential gradient of the surrounding sea. Data recording is done in conjunction with the ROV guidance systems; hence, the operators are able to map potential distributions along pipelines, platforms, and monopile foundations. CP integration into the regular ROV corrosion inspection facilitates the prompt detection of anode systems and coating damage in specific regions of cathodic under-protection or overprotection. Automating rudimentary inspections contributes a great deal to the corrosion integrity management procedures.

ROVs can deploy electromagnetic inspection tools like eddy current (EC) and magnetic flux leakage (MFL) sensors that are excellent for defect characterization and detection in conductive materials. In eddy current testing, cracks, pits, and materials with different properties are identified by changes in induced currents due to the presence of alternating magnetic fields generated in the metallic component, which is highly effective for surface and near-surface flaws for welds and tubular joints. Magnetic flux leakage tools magnetize ferromagnetic materials and measure the amount of magnetic field distortion caused by corrosion or loss of wall thickness in the material. These methods are optimum for finding defects that are covertly located under layers of coatings or under marine growth, which visual inspection fails. Integrated with ROVs, these methods enable accurate and controlled positioning along and around pipelines, risers, and structural node points to augment the UL and visual inspection frameworks with additional assessment and diagnostic capability (Abu Zeid and Elshahawi, 2023; Cheramie and Anderson, 2023).

The mapping functionality of ROVs has been enhanced by the use of laser scanning as well as sonar mapping technologies. The laser range scanners attached to ROVs use beams of light and capture the reflections to determine the structure's geometry. This gives the thickness of the marine growth and helps in verifying the design against the snapshot of the structure. In visibly limited areas, laser sonars and scanning sonars work in conjunction to provide complementary mapping systems. ROV-mounted sonars rapidly identify scouring, sedimentation, and undersea wrecks while swiftly scanning large areas. By merging the laser and sonar datasets, the ROV operators are able to create and work with detailed digital twins of the subsea infrastructures. These lasers fulfill the requirements for the structural simulations, hydrodynamic analyses, and other methods to determine the long-term integrity of the structures. Moreover, these methods also provide essential inputs to the automated change detection algorithms, enabling operators to quantify reduction trends.

Offshore asset integrity management is revolutionized by combining ROVs with sophisticated inspection technologies. ROVs are versatile, safe, and economical. From simple visual observation to more advanced NDT methods like ultrasonic (UT) scanning, electromagnetic methods, and 3D laser-sonar mapping, ROVs are capable of advanced inspection NDT. In addition, advanced inspection technologies improve by supporting workflows in digital photogrammetry, corrosion mapping, defect and digital twin workflows, as well as enhancement workflows in structural analysis, defect mapping, and characterization. integrations with artificial intelligence offer predictive maintenance modules (Nauert and Kampmann, 2023; Tidey *et al*, 2023). ROVs are becoming more common as the industry requires more ROV-based systems for offshore renewable energy and as the inspection systems demand more advanced automation and tight data integration. ROVs are becoming more common as the industry requires more ROV-based systems for offshore renewable energy and as the inspection systems demand more advanced automation and tight data integration. ROVs have unlimited potential as the inspection systems become more advanced. As the industry matures, ROVs will become more reinforced to ensure positive ROI on maintenance as well as operational ROI. ROVs have unrivaled potential for revolutionizing offshore asset integrity management as other operational systems become more capable.

2.3. Data Recording Systems for ROVs

The use of remotely operated vehicles (ROVs) in remote operations has changed how asset integrity is managed in both the renewable energy and oil and gas industries. ROVs offer an operational capacity in difficult subsea environments, and their primary usefulness is in gaining, storing, and analyzing high-quality inspection information, as shown in Table 1. The importance of the ancillary data recording, data structures, and processed information collected to support long-term decision making (Jahanbakht *et al*., 2021, and Schwing, 2023). These systems use real-time and post-mission data capture, sensor systems, complex metadata, and photogrammetry and 3D visualization. Spatial data/3D models generated using photogrammetry, which is a 3D visualization, visualization, and other integrity management elements of modern management systems.

Operation of ROVs has learning to adopt both data sets in capturing and recording another file, and in retrieving another file. Capture, which is the controlled component of the whole set, is the achievement of the other component, i.e., the achievement of using real-time video and sensor systems for MX and telemetry to system components, ROVs, remote capture, and use of assigned nodes.

Unlike mission data, where the focus was on the vital aspects of data captured, data captured after the mission is completed emphasizes the primary storage of data about raw sets for future analyses. Mission-concluding archives are processed and stored with high-resolution video, sonar images, and results of non-destructive tests (NDT) done during the mission. Comprehensive analysis that is not constrained by time during live operations fundamentally characterizes detailed approach trending studies, defect compliance, and regulatory analyses (Taylor *et al*., 2021). Post-mission workflows primarily enable these analyses. It is the combination of post-mission workflows with mission data analysis that allows for superior defect characterization and regulatory compliance trending studies. Flexible real-time post-mission interactivity and post-mission, not including any interactivity, both enhance the approach that needs to be taken for optimization in inspection data and data quality logging.

Modern ROVs are equipped with high-definition cathodic protection probes, ultrasonic, and sonar ranging with video data, and the telemetry associative streams data recording units integrate these along non-homogeneous architectures. Video with associated ultrasonic reading captures footage that aids in locating defect sites on risers or pipelines in real time. Context that is additional context is provided vis-à-vis the telemetry data, which enhances the findings of the inspection. This includes depth, orientation, along with the bearing of assets, and the position relative to the assets.

Table 1: Data Recording Systems for ROVs

Theme	Key Aspects	Benefits	Challenges
Real-Time vs Post-Mission Data Capture	- Real-time data transmission for onshore monitoring. - Post-mission high-resolution data review. - Dual storage (edge + cloud) for redundancy.	- Enables immediate decision-making during missions. - Provides detailed records for retrospective analysis. - Enhances operational flexibility.	- Bandwidth constraints for real-time streams. - Post-mission review may delay anomaly detection. - Increased storage requirements.
Integration of Sensors with Video and Telemetry Streams	- Synchronization of sonar, acoustic, ultrasonic, and visual data. - Embedding telemetry (position, depth, orientation) into video feeds. - Multi-sensor fusion dashboards.	- Rich, context-aware inspection datasets. - Improves the accuracy of anomaly localization. - Supports automated AI-based defect detection.	- Complex system calibration and synchronization. - Potential data overload. - High integration and maintenance costs.
Use of Structured Metadata and Inspection Logs	- Tagging datasets with asset ID, GPS coordinates, defect type, and inspection conditions. - Standardized digital logbooks. - Compatibility with international inspection databases.	- Enhances traceability and comparability across missions. - Facilitates regulatory compliance and audit readiness. - Enables big-data analytics for predictive insights.	- Metadata gaps in legacy records. - Human error in manual logging. - Need for consistent international standards.
Photogrammetry and 3D Reconstruction for Historical Comparison	- High-resolution 3D models built from ROV imagery. - Baseline comparisons with previous inspections. - Integration with digital twin platforms.	- Enables precise defect growth tracking. - Long-term historical record of asset condition. - Supports immersive visualization for training and planning.	- Computationally intensive processing. - Accuracy depends on image quality and stability - Requires skilled interpretation and specialized software.

The use of multiple types of sensors within a single system decreases uncertainty relating to defect recognition and increases the traceability of all accessed data. (Babalola *et al*., 2024). Improvements in data fusion algorithms make it possible to automate the registration of sensor outputs. This improves the efficiency of the inspection process by reducing the amount of manual labor needed. As the complexity of offshore buildings increases, systems that integrate multiple sensors will become essential for creating reliable and useful data sets.

An important part of the data captured by the ROVs is the structured and purposeful use of accompanying metadata and the inspection book that describes the work completed. This metadata is the information captured that describes the context in which the data was collected. This can include data and time, the name of the asset, the sensor used, the conditions of the environment, and notes from the operator. By attaching metadata to the inspection data, it is possible to arrange, create cross-campaign comparisons, and effectively manage the data from multiple inspections (Alfeo *et al*., 2021; Prodanović and Branisavljević, 2021). This organization assists with data-driven decision-making and improves the chances of regulatory requirements being met, as it eliminates the need for manually kept inspection records and safety records.

The logs themselves are made in parallel to videos and sensor data, telling the story of the mission in a step-by-step format. Usually, logs describe the route of inspection, items of interest captured, how each item operated, and what was done afterward. Combined with metadata, inspection logs become part of a holistic digital system for prolonged and improved strategy deployment monitoring, ease of data access for more simplified trending, and improved decision-making for an entire mission.

Referring to the enhancement of ROV data recording, the use of photogrammetry and 3D reconstruction stands out. Subsea assets are modeled photogrammetrically by capturing still pictures at different angles and perspectives. With the addition of specialized video and sensor data, photogrammetry can create digital twins of infrastructure components, such as wind turbine foundations, pipelines, and manifolds.

These components are invaluable three-dimensional models as they serve as historical baselines on which future inspections can be made. Continuous surveying of a pipeline over time can identify regions of increasing corrosion, coating deterioration, and movement within the seabed. Likewise, 3D reconstruction of the wind turbine foundations can be used to assess the growth of scour pits over time, along with the accumulation of marine growth (Sarmiento *et al*., 2021; Barros and Matos, 2023). With the support of temporal comparison and change detection, maintenance and repair strategies can be improved as better predictions on asset deterioration can be made with the help of operators.

Including ROV photograms into the workflow substantially enhances the data provided to increase understanding of more complex aspects of inspections, which can be provided to engineers, the regulators, and even less technical supervisors. ROV photogrammetry greatly improves the end of the workflow by allowing the transition from 3D models to an emphasis on the operational aspects of the data to refine strategies and plans for field engagements.

The pivotal role of data recording systems in fully realizing the potential of ROVs in ROVs within offshore settings is particularly salient. The real-time mission data capture and post-mission data capture processes are used while integrating the varying data into relevant contexts. The methodically planned and executed inspection logs and structured metadata usage increase compliance, traceability, and long-term monitoring. On the other hand, photogrammetry and 3D reconstruction are groundbreaking methods for predictive maintenance and historical analysis. All of the functions of the ROVs propel them beyond conventional inspection devices to advanced data-gathering systems vital for asset integrity management. The continued advancement of ROV data recording systems will enhance the safety, efficacy, and eco-friendliness of offshore operations. The offshore industries are set to benefit from the sophistication of ROV data recording systems for enhanced predictive and digital operations. Schwing (2023) and Mohsan *et al*. (2023) confirm the sustainability of these systems.

2.4. Inspection and Asset Management Software

The nuance in offshore renewable and the oil and gas industry has increased the need for detailed asset management and inspection software. The issue lies in the inspection and validation of offshore networks comprising subsea pipelines, platforms, wind turbine foundations, risers, and other renewable assets, as well as inspection data collection and the validation, structuring, and analysis of intelligence data (Velenturf *et al*, 2021; Cullinane *et al*, 2022). The SENSE software, along with FDVR (Field Data Validation and Reporting) and COABIS (Computerized Offshore Asset Base Integrity System), exemplifies how inspection data can be transformed into asset integrity frameworks, as shown in Figure 2. These assets together enable data-driven decision-making and risk-based inspection in the offshore industry, with a focus on predictive maintenance and structured reporting, historical analytics, and maintenance integration.

Fig 2: Inspection and Asset Management Software

FDVR offers digitized reporting and inspects data collected during surveys utilizing ROVs, diver surveys, and campaigns for non-destructive testing to streamline them into an easy and standardized, recoverable format. Through the use of standardized formats and validation tiers, FDVR can reduce human error, remove data redundancy, and work seamlessly with enterprise asset management systems. It is especially evident in the system that features inspectors, who capture reliable data regarding the corrosion of mapped walls, the condition of their welds, and the potential of cathodic protection. The core of FDVR's functionalities is in the features that provide real-time validation, able to capture incomplete, inconsistent, or unusual data before submission to maintain the records of the inspections. This serves as the core of the analytics waiting to be built in the future. As noted in the work of Handley *et al.* (2022) and Hoehle *et al.* (2022), the confidence in asset reports within the industry can rapidly improve alongside the uncertainty, and costs associated with the inspections can be streamlined with the use of the FDVR's workflows."

Broader than mere inspection data platforms, COABIS is a fully integrated system for managing asset integrity. Constructed to combine and track data for multiple inspections throughout the lifecycle of an asset, COABIS offers engineers a historical database for identifying and monitoring degradation trends over time. This is invaluable in the assessment of corrosion and the effectiveness of mitigative processes through the correlation of ultrasonic tests with cathodic protection surveys. In addition to this technical data, COABIS provides essential compliance management. COABIS users must comply with certain standards, such as the ISO 19901, the API RP 2SIM, and any I Permit national offshore safety guidance, particularly offshore operators. COABIS aids in monitoring compliance automatically by associating inspections with observations of non-conformance or overdue surveys to regulatory guidelines. This is mostly helpful in large offshore portfolios where maintaining compliance for hundreds of assets is an operational difficulty. COABIS is able to combine inspection records, risk-based assessment, and compliance metrics to support seamless asset integrity management. This asset integrity management is achieved through optimized inspection intervals with reduced operational risk.

In contrast to FDVR and COABIS, which are targeted toward historical data synthesis and structured reporting, SENSE takes a novel approach to predictive and prescriptive analytics and is a next-generation asset management software. SENSE's ability to facilitate early anomaly recognition in corrosion and weld defects, as well as structural deformations (Madhvacharyula *et al.*, 2022; Shang *et al.*, 2023), is accomplished through machine learning models amalgamated with inspection data. These models, trained on historical datasets, are capable of detecting condition monitoring baselines that fall outside of condition monitoring thresholds. SENSE's ability to integrate predictive maintenance is a key novel feature of SENSE. SENSE enables remaining life estimates and dynamic risk assessment and thus supports inspection data with environmental data, operational loads, and digital twin data. This allows operators to shift their strategies from reactive maintenance but condition-based maintenance. SENSE generates predictive analytics in a manner that reduces unplanned downtimes, improves safety margins, and increases the life cycle of assets.

FDVR, COABIS, and SENSE have integrated platforms, highlighting the usefulness of digital technologies in risk-based inspection (RBI) and decision-making. Traditional inspection management often struggles with unintegrated datasets, poor traceability, and planned maintenance. A digital platform closes this gap with standardized, approved, and historically validated inspection records along with probabilistic risk models. These models mathematically predict defects, failures, and their repercussions, enabling the prioritization of high-stakes risk models and efficient allocation of inspection resources. Decision-makers utilize dashboards and scenario analyses to evaluate asset degradation trends and compare inspection results across entire asset fleets. The addition of SENSE predictive analytics allows operators to shift maintenance strategies that comply with operational and regulatory requirements.

As a key element of offshore integrity management and offshore asset management, inspection and asset management software has matured significantly in recent years (Adewoyin, 2022; Ramis *et al*., 2023). Platforms like FDVR, SENSE, and COABIS data and streamline the inspection data to provide insights and predictive maintenance, while COABIS archives the data for future compliance reporting and facilitates inspection reporting. All these frameworks allow data to facilitate the strategic decisions required to ensure economic sustainability and safe operation of the offshore assets. Defining these digital tools in a risk-based inspection framework enables operators to enhance their asset investment strategies while also improving lifecycle compliance management with global safety regulations. With the use of offshore assets expanding to renewables, the need to improve the flexibility, reduce the maintenance downtime, and strengthen the guidance provided to asset integrity managers has made the adoption of such software systems critical.

2.5. Case Studies and Applications

In the case of Remote Operated Vehicles (ROVs), user-assigned goals often include high precision loyalty inspections, maintenance, detailed information collection, and asset integrity management, as well as the collection of information on areas and particulars that are lacking human access, such as via a diver. ROVs offer such context and value in the asset integrity management of the offshore, as the oil and gas as well as the renewable energy sectors deal with structural fatigue, corrosion, and degradation of subaqueous infrastructure. More, ROVs do not just carry on inspections, as ROVs coupled with digitized technology allow for optimizing predictive maintenance levels and long-term performance of an asset (Medagoda *et al*., 2022; Damian-Serrano *et al*., 2022). These include the development of digital twin models that serve in monitoring offshore wind turbine foundation models, and pipelines with augurs.

ROVs serve with role with offshore wind farms, as with the introduction of turbines, the need for reliable monitoring techniques on turbine foundations is growing. Monopiles and jacket foundations are exposed to the encroaching sea and hydrodynamic forces plus cyclic loading, and of key interest as well are the ROVs providing foundation inspections via visual surveying and ultrasonic thickness inspection, and photogrammetric mapping.

As an example, in the execution of large European wind farms, observation-class ROVs have been utilized to conduct periodic inspections of the monopile foundations. ROVs with high-definition cameras and sonar imaging are able to detect the early stages of corrosion, scour development around the seabed, and welded joint fatigue cracks. ROVs have been valuable in developing the photogrammetric technique in constructing 3D models of the bases of the foundations, which enables the operators to determine the variance in structural conditions across multiple inspection campaigns. This allows for proactive measures to be taken, such as scour protection reinforcement and targeted repairs, which help in enhancing the asset's service life and the reliability for power generation. (Sasidharan *et al*. 2022; Gidiagbaa *et al*. 2023).

Furthermore, the combination of ROV surveys with environmental monitoring adds supplementary value. ROVs assess scour protection effectiveness, marine growth, and compliance with the environmental impact assessment. This comprehensive approach highlights the importance of ROVs in both the engineering and ecological aspects of offshore renewable energy.

ROVs are vital to the oil and gas industry in deepwater fields for inspections of subsea pipelines and risers. Pipelines and risers are critical for the continuity of production as they have the functions of transporting hydrocarbons to processing facilities and connecting the subsea systems to surface platforms, respectively. Both systems are prone to corrosion, fatigue, and external damage.

In the Gulf of Mexico, work-class ROVs are deployed to monitor the condition of pipelines laid at depths greater than 2,000 meters. These ROVs autonomously execute corrosion mapping, using high-resolution probe cathodic protection sensors, in association with free span corrosion monitoring over the bottom in motion. They also document the condition of the pipe protective coating by monitoring negative ROVs tracking through Real-time high-definition video. ROV inspection engineering inherently separates ROV inspection from project inline inspection, undermining project inline inspection diagnostics, confirming visible scarring from trawling, and coating disbandment.

In the case of risers, ROVs are also gaining benefits. With ROVs, the complicated process of assessing the wall thickness and the quality of longitudinal and circumferential welds possesses greater precision due to the employment of eddy current testing and ultrasonic testing mounted on ROVs. When data is captured in the region of critical fatigue load vertices, active prediction of the failure can be exercised by scheduling repairs for replacement. Additional ROV advantages to carrying heavy manipulators enable tasks like the blind installation of aux confinement dominated assembly clamps, the cleaning of flexible marine growth, and the operation of subsea valves (McConnell *et al*., 2022). With their greatly increased versatility, ROVs are critical to sustaining the reliability of production and greatly reducing the risk of environmental accidents during deep-water operations.

One unique application of ROV technology is in the synthesis of inspection information with Digital Twin technology. Digital Twin is a technology that creates digital replicas of real assets, incorporating data streams. The replicas can incorporate real-time data streams and historical data for monitoring and can use the data for simulation and predictive analytics. ROVs are used a primary data acquisition system and provide digital twins with information related to the structure's condition, the environment, and operational performance.

In offshore wind farms, ROV photogrammetry models of foundation systems have been incorporated in digital twins for simulating scour and fatigue behavior. These models help operators to estimate the rate of deterioration, improvement in maintenance schedules, and reduced downtime. For example, offshore in a (???) wind farm, repeated ROV surveys can be used to assimilate a digital twin and provide reconstructed structural measurements that help to test multiple mitigation techniques in a simulation to identify the most effective ones for real-world application.

In the oil and gas sectors, integrated ROV inspection data with pipelines and risers to create digital twins for improving risk-based maintenance planning. Rodrigues *et al*, 2023. Igbadumhe and Feijo, 2023. Combined with ultrasonic and cathodic protection readings, flow dynamics, and other environmental models to predict rates of corrosion, fatigue life, and growth. This facilitates predictive maintenance, therefore decreasing maintenance and inspection costs, as well as avoiding unscheduled outages. The integration of digital twins with complex subsea structures provides for greater stakeholder engagement and, therefore, stronger communications with regulators, engineers, and engineers, as well as other decision makers.

ROVs focus on offshore asset management for both renewable and oil and gas sectors. ROVs efficiently offer reliable and high-quality data for maintenance and risk mitigation when monitoring turbine wind foundations, pipelines, and risers in deepwater fields. In addition, ROV data integrated with digital twin models offers more than inspection; predictive asset life cycle management and operational cost insights. These integrations showcase ROV's importance beyond inspection as data ecosystems for ROV-derived offshore energy infrastructures. The ROVs contribute to data-driven approaches for resiliency and sustainability.

2.6. Challenges and Limitations

The remote inspection technologies and digital interfaces have advanced in leaps and bounds. However, it is a paradox that the use of Remote Operated Vehicles (ROVs) and their integrated asset management systems is still sub-optimal. There persist some challenges (s) that impact it negatively, as shown in Table 2 (Rinaldi *et al*., 2021; Poggi *et al*., 2021). These include, but are not limited to, the impact of the operational and physical environment, a vast array of inspection data and their assimilative management, the use of nascent Artificial Intelligence (AI) and Machine Learning (ML) systems, and the training and certification hurdles of the workforce. Autonomous management of these issues is vital as well as a prerequisite to achieve desired reliability, cost reduction, and risk mitigation during offshore integrity management.

Not unlike the approach taken with rig and platform industry with the addition of workboats and ROV's launched from the surface, and integrating deep water complexities of tethered and free, the calculus of offshore inspection also is heavily influenced by the mutable coordination of inspection, time and depth, with optimum weather and current conditions, leash and tether, and wave indifference set as mutual thresholds for cost and resource conservancy. It is normal with ROV work that the window for surface launch is high. Adding the unmanned aerial vehicles and surveillance drones added great flexibility to the approach and timing with aerial resource light conditions. Artificial intelligence makes inspection and pattern recognition easily documented, and overlaps with the cost of ROVs and photogrammetry. ROVs and light work supply acceptably low requirements for water clarity. Emergent sediment plumes with high plankton concentrations froth are the nemesis of photogrammetry. Work-class ROVs drop out of profitability when tethered below 300 meters, give or take 0.4 at 300 to 500 meters, due to the steep ascent costs driven by the tethers themselves. That is an underwriting restraint that needs prediction cross-course outcomes or also portfolio multiuse metrics measure taken reversely and globally to likely reduce the scope in an integrated Canadian and Mongolian sectorization, operably with low water and low plankton strategies targeted, and assuming operational water depths over 2500 meters as optimal.

Table 2: Challenges and Limitations

Challenge Area	Key Aspects	Impact / Consequences	Mitigation Strategies
Operational Constraints	- Adverse weather conditions affecting ROV/AUV deployment. - Water turbidity reduces visibility. - Depth and pressure limitations for equipment.	- Delays or cancellations of inspections. - Reduced quality of visual or sensor data. - Increased operational risk and cost.	- Schedule inspections during favorable conditions. - Use advanced sensors (sonar, acoustic imaging) for low-visibility environments. - Deploy deep-rated equipment with robust engineering.
High Data Volume Management and Storage	- Massive amounts of video, sensor, and telemetry data. - Need for structured storage and quick retrieval.	- Data overload can slow analysis and decision-making. - High storage costs and potential for data loss.	- Implement cloud-based or hybrid storage solutions. - Use data compression, filtering, and edge preprocessing. - Establish metadata standards for indexing and retrieval.
Integration with AI/ML for Automated Defect Recognition	- Linking multi-sensor data to AI/ML models. - Ensuring algorithm accuracy and reliability.	- Risk of false positives/negatives in anomaly detection. - Dependency on high-quality training datasets. - Complexity in system maintenance.	- Continuous model training with diverse datasets. - Human-in-the-loop verification for critical decisions. - Use multi-sensor fusion to enhance detection accuracy.
Training and Competency Requirements for Operators	- Skilled operators required for ROV/AUV control, data interpretation, and AI-assisted inspection.	- Workforce shortages or insufficient competency may reduce inspection quality. - Risk of operational errors or misinterpretation of results.	- Structured training programs and certification (BOSIET, ROV operator licenses).- Ongoing competency assessments and simulation-based learning. - Knowledge transfer from experienced personnel to new operators.

Today's ROV inspections produce astonishing quantities of data. Each inspection ROV captures records of images, scans, profiles, maps, and different readings, which, when combined, reach terabyte levels of storage. This excess bundle of data, along with storage and management data, poses a challenge of immense magnitude. Transmitting data to shore facilities offshore is also a major issue, along with real-time data storage and post-processing. ROV inspection records must meet regulatory compliance, which requires lifecycle management of retained data. Processes which suffice ensuring data accuracy, suppression of duplication, and resolved vaulted storage put stress on a resource. Data complexity, which stems from heterogeneity in collapsed and unstructured, numeric or video records, makes aggregation on centralized digital platforms a challenge. Operators risk information blindness, which would otherwise help in a practical scenario of inspection with the data compression and curation guidelines.

Combining tools such as artificial intelligence and machine learning with workflows for inspection has great possibilities for automating anomaly and predictive analytics and defect recognition. Nonetheless, the practical application has serious constraints. Offshore domains, due to proprietary limitations and discrepancies in inspection quality, often lack large, high-quality labeled datasets essential for training robust AI/ML models. The diverse nature of subsea environments makes it even more difficult the generalization algorithms as models trained in one region or asset type perform poorly in another. On the other hand, the limited computing capacity available on ROV platforms for real-time onboard processing constrains the portability of high-end algorithms in offshore conditions. Moreover, the transparency and trust of inspection outcomes for compliance regulations or maintenance works are a major concern due to the specialized nature of the AI models. Once these limitations are handled, AI/ML integration will remain as a supplementary aspect rather than the primary focus in offshore inspection workflows.

The role of humans is still paramount in the effective use of ROVs for inspections and digital integrity management. The operation of complex ROVs and the interpretation of complex data from inspections is a trained, certified, and technically competent specialization. They are proficient in piloting and sensor operation, non-destructive testing, and software tools such as FDVR, COABIS, or SENSE. Errors in data collection, such as failing to derive meaning from an inspection or using unsatisfactory digital tools and technologies, are largely attributed to training deficits (Avula, 2021; Engelen *et al*, 2021). AI and predictive analytics technologies increase the need for hybrid skillsets, wherein data science is interlaced with domain expertise. In the offshore industry, high turnover rates and the cost of perpetual training programs are significant challenges to workforce development. The use of advanced inspection technologies is rendered meaningless by human underdevelopment from unsustained structured competency frameworks and development investments.

The use of ROVs for inspections and digital asset management technologies is limited due to environmental, technological, and anthropogenic issues. Operational issues like weather impact, water turbidity, and depth affect inspection window availability and data acquisition quality, while the vast and heterogeneous datasets impede long-term integrity management. The use of AI and ML technologies integrated into inspection workflows is promising, but is restricted by limited datasets, reliance on computational power, and regulatory issues. The fact that easily achievable tasks do rely on digital XXI-trained professional points to the lack shag AI sophistication. (Abdulkareem *et al*., 2023; Akande *et al*., 2023). Solving these problems at once does require a combination of innovation in data frameworks, operational strategies lacking infrastructural resiliency, and development of adaptable, highly educated personnel. Only through such a combination can the offshore industry exploits the full breadth of ROV inspection technologies to safely sustain the integrated inspection of underwater assets.

2.7. Future Outlook

The incorporation of Remote Operated Vehicles (ROVs) on offshore assets has a significant impact on emerging frameworks around automation and asset management, as shown in Figure 3. Inspection functions are likely to evolve with the continued integration of ROVs into offshore operational ecosystems, achieving greater levels of independence and self-sufficiency. Collectively, innovation in sensor autonomy and regulatory frameworks on pollution is likely to shift the paradigm on the management of offshore assets (Rehan, 2021; Rane *et al*., 2023).

An emerging ROV-ROV system is the hybrid autonomous underwater vehicle, a system that possesses both real and imagined ROV functions. These vehicles are able to carry out real-time navigation using ROVs and carry out autonomous endurance functions with the AUV. A dramatically reduced need for surface vessels and ROVs is predicted for new, remote offshore sites such as floating wind farms or deepwater oil and gas fields.

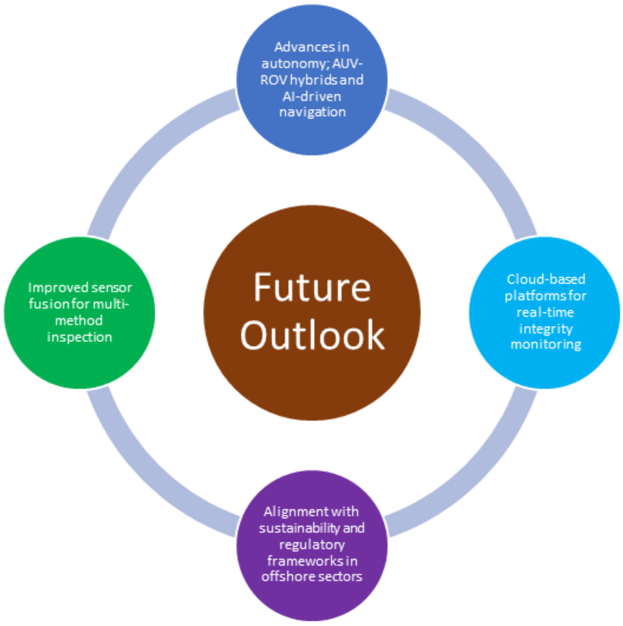


Fig 3: Future Outlook

The artificial intelligence (AI) technology of on-board navigation is also progressing, allowing ROVs to identify and respond to changing environmental conditions such as currents, visibility, and other unanticipated barriers. Machine learning techniques can analyze sensor data as it is collected to optimize inspection paths and improve overall productivity. Automated defect recognition, in which AI systems inspect video and sonar records to find other pieces of corrosion, fractures, and failures in coating, will enhance inspection workflows further by lowering the burden of human judgment, increasing repeatability, and reducing interpretation errors (Li *et al*. 2022, Sharifisoraki *et al*. 2022). In the future, ROVs will feature advanced algorithms that enable sensor fusion— the integration of different inspection techniques within a singular framework. Inspections in the current paradigm still require multiple deployments to capture video, sonar, ultrasonic data, and perform cathodic protection tests. Cross-domain sensor integration will capture and align multiple data streams in a single deployment, achieving a more advanced comprehension of asset condition. (Akande *et al*., 2023; Abdulkareem *et al*., 2023;)

For instance, combining ultrasonic measurements of thickness with 3D photogrammetry will offer the region of interest defect metadata along with a contextual global structure. Also, the integration of advanced cameras with acoustic emission sensors could result in the real-time tracking and visualization of fatigue crack propagation. Sensor fusion addresses the issues of tardiness, duplication, and systematic errors, and thus greatly increases the reliability of defect detection and prediction of the system's lifecycle. (Babalola *et al*., 2024). The offshore digital operations are propelling the use of data processing cloud platforms. These platforms handle enormous volumes of ROV data. Directly Monitoring the Integrity of a Structure (DMIS) real-time offshore and onshore data capture, and cloud data server inspection enable data transmission from remote sites. Engineers and global stakeholders can access the insights and visual results on demand (Pillai, 2022; Steen *et al*., 2023).

Cloud technology enables real-time digital twin technology. With cloud technology, new inspection data is refreshed continuously. (Jiang *et al*., 2021). These cloud platforms are constructed on a real-time basis. Digital twins allow the operators of the vessel site to plan, schedule maintenance, and implement procedures without direct application of the physical systems. In addition, cloud technology provides the use of assets remotely. These assets can be used from different locations. This enhances inter- and intra-organizational systems of knowledge transfer.

With increasing global focus on sustainability, offshore energy sectors continue to streamline operations while considering their environmental and social impact. ROVs and their sustainability and compliance frameworks will continue to evolve. ROVs significantly lower carbon footprints associated with offshore operations by reducing the need for diver interventions and attendant vessel deployment times (Swain *et al*. 2022; Newman *et al*. 2023).

As part of the regulations, ROVs will be critical to ROV with regard to compliance and environmental impact on the works being done and within the ROVs. Enhanced data traceability through cloud systems with structured metadata makes transparent reporting within compliance and to stakeholders tangible. ROVs carrying environmental monitoring instruments also produce data on biodiversity, changes to the seabed, and waters within which the ROVs function, contributing to ROVs and engineering ecosystem integrators and sentinels (Glaviano *et al*, 2022; Bogue, 2023).

The increased focus on ROV operations to integrate sustainability is part of the wider focus on environmental, social, and governance (ESG) criteria for performance in the offshore areas (Bril *et al*. 2022; Martto *et al*. 2023). ROVs are unable to perform inspection and monitoring works to assist with compliance with the growing regulations set by governments and global entities on carbon emissions and ocean sustainability to promote safe and responsible energy extraction and works.

Future developments and uses in ROVs for offshore asset integrity will incorporate more autonomy, smarter sensor integration, increased digital connectivity, and enhanced alignment with sustainability frameworks. A hybrid AUV-ROV system with AI-driven navigation will minimize operational costs and risks while enhancing inspection sensor integration. Cloud technologies, coupled with inspection predictive maintenance, and digital twin development, will foster real-time intelligent inspection data (Agostinelli, 2021; Hakimi *et al*., 2023). Finally, ROVs embedded in sustainability and regulatory frameworks ensure that offshore industries meet economic and environmental targets. These will reposition ROVs from inspection instruments to key, omnipresent, resilient, digital, and sustainably integrated offshore structure enablers.

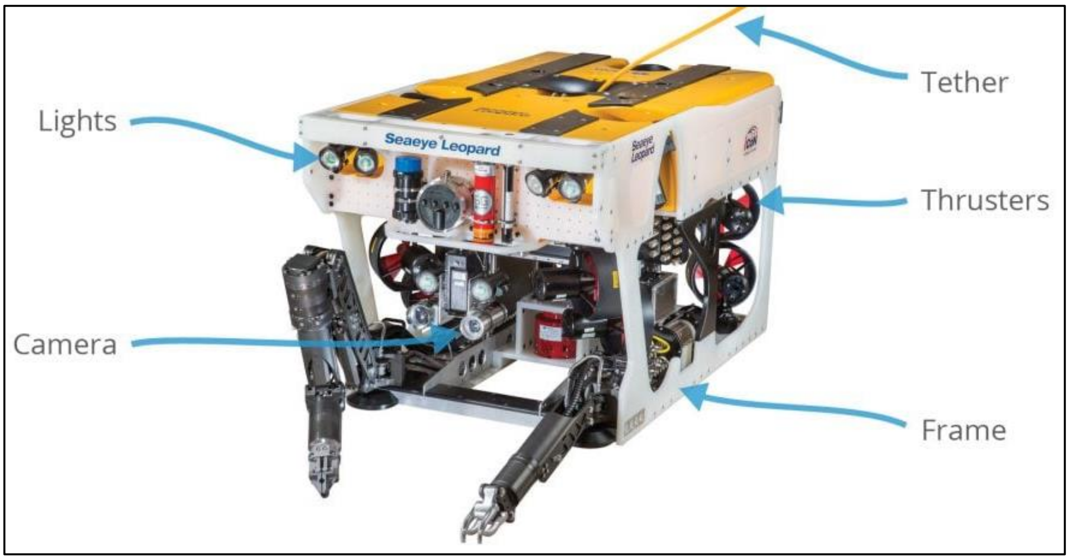
3. Conclusion

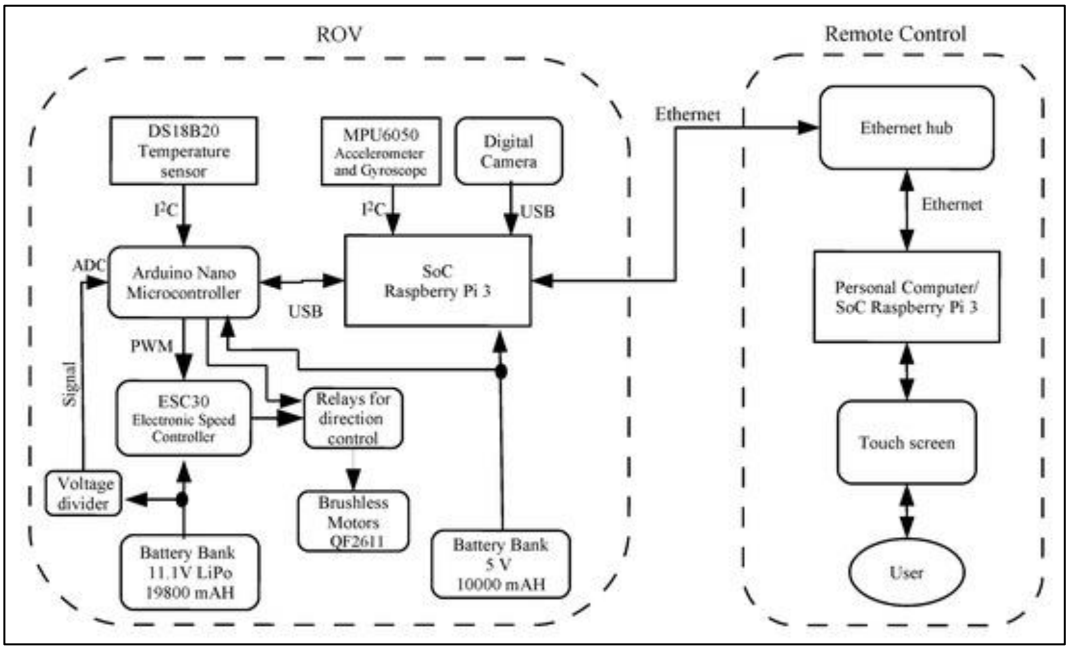
Remote Operated Vehicles (ROVs) have been crucial in preserving the integrity of offshore assets within the commercial as well as the renewable energy sectors. It can work in hazardous and deep-water conditions, making it safer as well as more efficient when compared to diver inspections. It is more versatile than the traditional methods of inspection. ROVs are able to conduct ultrasonic tests, cathodic protection probes, and laser and sonar mapping systems, along with monitoring corrosion, validating protective systems, assessing marine growth, and performing flaw detection through advanced ROV inspection payloads like photogrammetric as well as high-definition cameras. This ensures the offshore wind turbine foundation remains stable for the long run and serves as a crucial point for extending the operational life of subsea pipelines, risers, and platforms in the oil and gas sector.

The integration of ROVs with software tools that manage data preservation and asset integrity amplifies the effectiveness of ROV inspection services. Tools like FDVR maintain data consistency and reliability validation of field data. COABIS provides compliance monitoring and historical data tracking. Emerging systems like SENSE transform inspection data into intelligence techniques using advanced analytics systems and predictive maintenance frameworks. This approach, where hardware technologies are merged with digital Ford systems, shifts maintenance practices from reactive strategies to more risk-predictive strategies, decreasing system downtime and increasing safety margins.

Honed down to the future, the integration of ROVs with offshore frameworks in terms of refinement and eco-sustainability will continue to dynamically change. ROV incorporation with artificial intelligence, self-governing systems, and digital twin technologies will enable them not only to inspect but also to perform real-time asset control and decision-making optimization. With the rapid increase in scale and complexity of offshore infrastructure, ROVs will continue to be instrumental in operational reliability, environmental protection, and the critical energy systems.

4. Appendix





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