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Development of autonomous underwater vehicles for inspection and loss prevention in subsea oil and gas operations

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Abstract

Autonomous Underwater Vehicles (AUVs) have become increasingly important in the oil and gas industry for performing inspection and loss prevention tasks in deepwater operations. By reducing human involvement in hazardous environments, these vehicles offer significant advantages in cost, safety, data quality, and operational flexibility. This research provides a comprehensive review of the development of AUVs and their application in subsea oil and gas operations. It covers historical milestones, enabling technologies, current industry deployments, challenges, and emerging trends. The review highlights how advancements in battery technology, navigation systems, sensor capabilities, and artificial intelligence have collectively propelled AUVs to become indispensable tools for offshore asset integrity management.

Keywords: Emerging Technology; Subsea Inspection; Autonomous Underwater Vehicles; Deepwater; Offshore

1. Introduction

Subsea oil and gas operations play a pivotal role in meeting the world's energy demands, with a significant portion of global hydrocarbon production now occurring offshore often at great depths and in remote regions [1, 2]. The infrastructure supporting these operations is extensive, encompassing wellheads, manifolds, pipelines, risers, subsea processing units, and various other systems. These assets must withstand harsh oceanic conditions, including high hydrostatic pressures, strong currents, corrosive saltwater, shifting seabeds, and marine life fouling [3, 4]. Even minor structural or functional failures can lead to significant economic losses and pose considerable environmental risks in the form of hydrocarbon spills or gas leaks [5].

Historically, inspection and maintenance of subsea infrastructure have been carried out by diver teams and Remotely Operated Vehicles (ROVs). While effective, these methods come with notable drawbacks. Diver-based operations are limited by depth and time constraints related to human physiology, and they place personnel in inherently hazardous environments [6, 7, 8]. ROVs, despite eliminating direct human exposure to deepwater conditions, still require dedicated surface vessels, large crews, umbilical cables for power and control, and continuous human oversight, leading to high operational costs. Additionally, rough seas, complex currents, and visibility challenges can impede both diver and ROV performance, necessitating advanced planning and sometimes extended downtime [9, 10].

Against this backdrop, Autonomous Underwater Vehicles (AUVs) have emerged as a transformative technology. Initially developed for scientific exploration such as mapping ocean floors or studying marine ecosystems AUVs have steadily evolved in both design and functionality [11,12]. Advances in materials, underwater navigation, computing power, and

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sensor technology have converged, allowing AUVs to tackle complex tasks that were once the exclusive domain of manned diving missions or tethered ROVs [13,14]. Today's AUVs feature robust propulsion systems, high-accuracy navigation tools (e.g., Doppler Velocity Logs, Inertial Navigation Systems, and acoustic positioning), and a variety of sensors capable of capturing detailed structural and environmental data in near-real time [15].

In the subsea oil and gas sector, AUVs are increasingly employed for asset inspection and integrity management, loss prevention, and environmental monitoring. Through advanced imaging and sensing (including high-resolution sonar, optical, and laser-based systems), AUVs can detect corrosion, cracks, or leaks in pipelines and other subsea equipment with great accuracy [16,17]. Furthermore, they can operate for extended periods without surfacing, reducing the need for large support vessels and minimizing overall operational costs. With growing environmental regulations and a global push toward safer energy production, AUVs are filling a critical niche by improving the efficiency and effectiveness of subsea inspections [18,19].

Nevertheless, significant challenges remain. Accurate underwater navigation without GPS, energy limitations tied to battery capacity, data handling for large-volume imaging and sensor outputs, and regulatory acceptance of fully autonomous technologies all impose constraints on large-scale adoption [20,21]. These issues are being addressed through ongoing research in areas such as artificial intelligence, subsea wireless communication, and novel power systems. Industry stakeholders, including major operators (e.g., Shell, BP, Equinor) and leading subsea technology companies (e.g., Kongsberg Maritime, Saipem, TechnipFMC), are investing substantial resources to refine AUV platforms, enhance sensor fusion capabilities, and develop standardized protocols for deployment [22,23].

This review paper offers a detailed examination of the development and adoption of AUVs within the oil and gas industry, particularly as they relate to inspection, loss prevention, and environmental compliance. It begins by outlining the primary vehicle designs and sensor technologies that enable high-quality data collection in deepwater environments. It then explores the operational benefits of integrating AUVs into subsea inspection workflows, illustrated by real-world case studies. Subsequently, it addresses the technical, economic, and regulatory challenges that may impede broader implementation of AUVs. Finally, the paper highlights emerging trends such as artificial intelligence-driven autonomy, subsea residency concepts, and multi-vehicle "swarm" approaches that could define the next generation of underwater robotics. Through this discussion, we seek to underscore the transformative potential of AUVs for offshore oil and gas operations, while acknowledging the hurdles that must be overcome to fully unlock their value.

2. Key AUV Technologies and Design Considerations

2.1. Vehicle Architectures and Propulsion

AUV architectures vary significantly to accommodate the diverse requirements of subsea oil and gas operations, where depth rating, mission duration, speed, and maneuverability all influence vehicle design. One prominent approach is the propeller-driven AUV, which typically relies on multiple thrusters for precise propulsion and control [24, 25, 26]. Such vehicles excel in deepwater environments that demand accurate station-keeping, allowing operators to carry out close-up inspections of complex infrastructure like risers, manifolds, and wellheads. Their capacity to hover steadily in water enables high-resolution imaging and laser scanning, making them especially valuable for detailed integrity assessments of pipelines or other critical assets [27,28].

In contrast, glider AUVs leverage buoyancy shifts and wing-like appendages to glide in a sawtooth pattern through the water column, reducing energy consumption and significantly extending mission endurance. While this buoyancy-driven approach renders them less adept at hovering or maneuvering around intricate subsea structures, it makes them highly efficient for wide-area tasks such as corridor mapping and pipeline route surveys [29,30]. By continuously adjusting their buoyancy, gliders can remain at sea for weeks or even months, collecting valuable data on seafloor characteristics and environmental conditions with minimal surface intervention. However, given their limited capacity for stationary flight, glider AUVs are more commonly employed for large-scale inspections rather than the high-precision, close-proximity examination of offshore equipment.

2.2. Sensor Suites and Data Acquisition

AUV-based inspections heavily rely on robust acoustic sensing technologies to map underwater environments and detect structural anomalies. Side-scan sonar (SSS) provides broad swath imaging, allowing for efficient detection of potential pipeline abnormalities or seafloor features that might compromise asset integrity [31]. Multi beam echosounders (MBES) extend these capabilities by generating detailed bathymetric maps, critical for pipeline route planning and identifying geohazards such as uneven seabed or scouring. For even higher-resolution imaging, synthetic aperture sonar (SAS) offers enhanced detail, enabling early detection of small cracks or corrosion on subsea structures and ensuring timely preventative measures [32].

Beyond acoustic methods, optical cameras and laser scanners are essential for close-range, high-fidelity inspections. High-resolution cameras often paired with LED or laser lighting capture detailed imagery of subsea equipment, revealing visible damage, marine growth, or compromised coatings [33]. Meanwhile, laser scanners measure the precise geometry of pipelines or risers, enabling operators to track subtle deformations or corrosion pitting over time. When visibility is limited due to turbidity, low-light and photogrammetry-based imaging systems can still provide critical information for asset integrity assessments [34].

Finally, AUVs maintain accurate underwater positioning through a combination of Doppler Velocity Logs (DVLs), Ultra-Short Baseline (USBL), Long Baseline (LBL) arrays, and Inertial Navigation Systems (INS), all of which compensate for the absence of GPS signals underwater [35,]. This precise localization ensures that inspection data is georeferenced for effective follow-up and maintenance planning. Meanwhile, environmental sensors including hydrocarbon sniffers and probes for temperature, salinity, turbidity, and dissolved oxygen augment the structural inspection data by highlighting potential leaks, water quality issues, or early indicators of environmental anomalies, thus playing a critical role in proactive loss prevention [36,37].

2.3. Autonomy, Control, and Data Handling

A key component of modern AUVs is automated mission planning, which allows vehicles to operate independently of human input for extended periods. In many applications, routes are pre-programmed and optimized to maximize coverage of specific areas, such as along pipeline corridors or around wellheads, ensuring consistent and repeatable data collection [38]. Advanced algorithms and onboard sensors also enable adaptive mission planning, where the AUV can adjust its path in real-time upon encountering unforeseen conditions such as unexpected obstacles, changes in seafloor topology, or dynamic ocean currents [39].

Equally important is real-time data processing, often underpinned by artificial intelligence (AI) and machine learning techniques. As the vehicle collects sensor data ranging from sonar images to optical camera feeds embedded AI algorithms can analyze the information immediately to detect anomalies, such as cracks, unusual seabed features, or potential leaks [40]. This onboard intelligence helps operators prioritize certain areas for closer inspection, curtailing time spent on post-mission analysis and accelerating decision-making.

Underlying these capabilities are communication and data handling systems that allow AUVs to share essential information with topside personnel or remote command centers, even when operating far below the surface. Given the bandwidth constraints of acoustic modems and underwater communication networks, most high-frequency or bulk datasets (e.g., high-resolution sonar, gigabytes of optical imagery) are stored locally for retrieval once the AUV surfaces or docks [41]. Meanwhile, low-bandwidth acoustic telemetry enables situational updates, such as vehicle status, basic sensor readings, and navigation corrections, keeping operators informed in near-real-time [42].

2.4. Energy Storage and Endurance

AUV endurance is fundamentally constrained by onboard power supplies, with lithium-ion and lithium-polymer batteries being the most common solutions. These batteries strike a delicate balance between energy density, weight, and operational safety, influencing not only how long an AUV can remain submerged but also how quickly it can move and how many sensors it can power simultaneously [43]. Current technologies enable mission durations ranging from a few hours to several days, largely dictated by the vehicle's size, propulsion demands, and sensor payload. While ongoing research focuses on improving battery materials and management systems, practical considerations such as thermal control, capacity fade over repeated cycles, and the need for robust safety protocols continue to shape how operators deploy and maintain battery-powered AUVs [44].

Beyond conventional batteries, fuel cell technologies offer promising avenues for extending underwater missions significantly, thanks to their higher energy density and potential for continuous power generation [45]. However, these systems are more complex and costly, requiring specialized fuel storage (e.g., hydrogen) and strict handling procedures to ensure safe operation. In parallel, the development of subsea docking stations has emerged as a key strategy for achieving near-continuous deployment [46]. By allowing mid-mission recharging or battery swapping, docking stations enable "resident" AUV concepts, wherein vehicles remain on the seafloor or attached to subsea infrastructure for extended periods. When paired with improved energy systems, these docking platforms can effectively transform AUVs into on-demand assets ready to perform inspections, environmental monitoring, or emergency interventions at a moment's notice.

3. AUV Applications in Subsea Inspection and Loss Prevention

3.1. Pipeline Inspection

Pipelines form the backbone of hydrocarbon transport from offshore fields to processing facilities, making their integrity paramount to avoid catastrophic environmental impacts and economic losses. In practice, propeller-driven AUVs equipped with high-resolution sonar, such as Synthetic Aperture Sonar (SAS) or Multi-beam Echo sounders (MBES), and optical cameras conduct systematic surveys to detect early signs of corrosion, pitting, or coating deterioration [47]. Beyond surface-level issues, these vehicles can spot free spans, where pipelines become unsupported due to seafloor erosion or shifting sediments, a risk factor for fatigue damage [48]. Furthermore, AUVs are particularly effective at tracking changes in pipeline burial depth and identifying sediment migration patterns, both of which affect pipeline stability [49].

3.2. Structural and Riser Inspections

Offshore platforms, risers, and manifolds endure constant stress from ocean currents, temperature fluctuations, and harsh environmental conditions, making regular integrity assessments crucial to avoid costly failures and potential safety hazards. AUVs excel in this domain by leveraging thruster-based station-keeping to maintain stable, close-up positioning while capturing high-resolution imagery of critical joints, welds, and structural components [50,51]. In parallel, laser scanning techniques enable operators to precisely measure any deviations or deformations in pipes and support elements, serving as an early warning against accumulating wear or corrosion [52].

3.3. Environmental Monitoring and Leak Detection

Beyond structural assessments, environmental monitoring is a critical function of AUVs in offshore operations, particularly for identifying and localizing potential hydrocarbon leaks. Equipped with specialized hydrocarbon sniffers and turbidity sensors, these vehicles can detect trace amounts of oil or gas before they reach hazardous levels, enabling rapid intervention to mitigate spills [53]. Optical cameras further enhance detection by spotting gas bubbles or oil sheens rising through the water column, a visual confirmation that often provides the precise location of a leak. In addition to real-time detection, AUVs collect comprehensive water quality data including temperature, salinity, and dissolved oxygen levels ensuring continuous oversight of environmental conditions [54,55]. Such capabilities not only aid operators in meeting regulatory standards but also minimize the ecological impact and financial repercussions associated with extended leaks or unplanned discharges.

3.4. Case Studies in Industry Adoption

Major oil and gas operators such as Shell, BP, and Equinor have reported remarkable success using AUVs for deepwater pipeline inspections in regions like the Gulf of Mexico and the North Sea. By leveraging high-resolution sonar and advanced autonomy, these vehicles can systematically scan long stretches of pipeline, collecting detailed data on structural integrity at more frequent intervals than was previously practical with divers or Remotely Operated Vehicles (ROVs) [56]. This improved inspection cadence has translated into reduced overall costs, driven by shorter vessel times, lower personnel requirements, and more proactive maintenance interventions. In turn, these outcomes lead to enhanced asset reliability and minimized environmental risks, underscoring the value proposition of AUV technology in large-scale subsea operations [57].

Another notable example is Saipem's Hydrone Program, which showcases the potential of hybrid AUV/ROV systems particularly the Hydrone-R model. Designed for both autonomous inspection and targeted intervention, the Hydrone-R can navigate subsea environments independently while retaining the ability to undertake tasks like valve operations when manual input becomes necessary. This dual-function approach is emblematic of an emerging trend in the industry, where multi-role subsea vehicles are increasingly sought after to handle a broader range of missions from routine asset integrity checks to urgent, unplanned interventions. As a result, the Hydrone-R exemplifies a next-generation solution that not only lowers operational costs but also extends mission flexibility in deepwater fields [58, 59].

4. Challenges in AUV Deployment

4.1. Navigation and Localization

Achieving accurate positioning and navigation in underwater environments remains a fundamental challenge for AUVs in subsea oil and gas operations. Unlike surface vessels that rely on satellite-based technologies like GPS for continuous georeferencing, AUVs must depend on acoustic positioning methods commonly Ultra-Short Baseline (USBL), Long Baseline (LBL), or short-range beacon systems. These techniques work by transmitting and receiving acoustic signals underwater, a process susceptible to signal degradation from factors such as absorption, scattering, and multipath reflections in the proximity of complex structures [60]. Consequently, acoustic-based location estimates can drift significantly if the signal paths become distorted or weakened, undermining the reliability of the data collected for integrity inspections and environmental monitoring [61].

To minimize these navigation errors, advanced sensor fusion approaches merge acoustic data with readings from Inertial Navigation Systems (INS) and Doppler Velocity Logs (DVLs) [62]. INS units track motion using onboard accelerometers and gyroscopes, providing a continuous estimate of position and orientation even when external references are briefly unavailable. DVLs further refine these estimates by measuring velocity relative to the seabed, mitigating drift when acoustic signals weaken. By integrating these data sources through sophisticated filtering algorithms such as extended Kalman filters AUVs can effectively compensate for the inherent limitations of acoustic navigation. This multi-sensor strategy not only reduces the impact of multipath disturbances but also enhances mission resilience, ensuring that critical inspection tasks are executed with consistent positional accuracy despite the challenges posed by deepwater environments [63].

4.2. Harsh Environments and Sensor Limitations

In many deep water and near-shore sites, turbidity and marine growth can severely hamper optical visibility, making it difficult for cameras and laser systems to capture clear, high-resolution images. Sub sea environments are often populated by algae, microorganisms, and sediment particles that can accumulate on lenses or scatter light, while marine organisms may cling to surfaces, obstructing both mechanical parts and sensors [64]. Over time, this bio fouling can degrade sensor performance and necessitate more frequent maintenance cycles. Such conditions pose challenges for operators who rely on precise visual inspections to identify cracks, corrosion, or other structural anomalies in underwater assets.

Adding to these difficulties, complex geometries around offshore platforms, risers, and pipeline networks can lead to sonar shadows and multi path reflections that complicate acoustic data interpretation [65]. Sonar signals may bounce off multiple surfaces, creating overlapping returns or gaps in datasets, both of which can obscure critical details. For example, pipelines laid in meandering routes across the seabed or located beneath large structural components can generate distortion effects that mask small defects or changes in sediment buildup [66]. As a result, operators must employ sophisticated data processing and filtering techniques often integrating inputs from multiple sensor types to mitigate these limitations, ensuring that AUV surveys deliver reliable, high-fidelity information for asset integrity assessments.

4.3. Energy Constraints

Despite ongoing advancements in battery chemistry and power management systems, energy availability continues to be a primary bottleneck in AUV operations. Most commercial AUVs rely on lithium-ion or lithium-polymer batteries that, although more efficient and safer than older battery types, still limit mission duration to a range of hours or days depending on vehicle size, propulsion requirements, and sensor payload [67]. Prolonged or complex tasks, such as detailed structural inspections or wide-area pipeline surveys, may exceed these time windows, necessitating more frequent surfacing or retrieval to recharge and thus increasing operational costs.

Compounding this issue is the fact that onboard sensors and thrusters can demand considerable power, especially when high-resolution imaging systems (like synthetic aperture sonar or laser scanners) and high-powered lights for visual inspections operate simultaneously. Rapid maneuvering in strong currents or precise station-keeping near subsea structures further intensifies energy consumption, trimming down the effective operational window [68,69]. While efforts are underway to develop alternative power sources, such as fuel cells or subsea docking stations that allow mid-mission charging or battery swapping, these technologies are not yet universally adopted. Consequently, efficient energy use, mission planning, and careful trade-offs between survey scope, sensor loadouts, and vehicle endurance remain critical considerations in AUV-based subsea inspection and monitoring strategies.

4.4. Data Volume and Management

The sheer volume of data generated by AUVs during sub sea inspections poses a formidable challenge for operators. High-resolution sonar scans, optical camera feeds, and environmental sensor logs can accumulate into terabytes of information over the course of a single mission. Storing this data efficiently requires robust onboard hardware capable of handling large data streams, as well as thoughtful mission planning to decide which datasets must be collected at the highest resolution and which can be sampled or compressed [70]. Additionally, managing the transfer and processing of this data is especially demanding in remote offshore environments, where bandwidth constraints limit how much information can be uploaded in real-time.

To convert raw sensor data into actionable insights, offshore teams must employ powerful analytic tools often aided by artificial intelligence and machine learning algorithms to quickly sift through large datasets and flag potential issues. Automated processes can highlight anomalies or defects that might otherwise be missed in manual reviews, enabling operators to make informed decisions about maintenance or intervention [71]. As autonomy increases, greater emphasis will be placed on real-time or near-real-time data interpretation, ensuring that critical findings are promptly relayed to onshore facilities or support vessels. This evolution in data handling underscores the importance of secure, high-capacity storage solutions and robust cybersecurity measures, both on the AUV and within the broader offshore communication network [72].

4.5. Regulatory and Safety Frameworks

Subsea robotics operate within a strict regulatory landscape, governed by organizations like DNV, API, ISO, and regional maritime authorities. These bodies mandate rigorous testing, certification, and risk assessments for any new technology introduced to offshore operations, ensuring that potential hazards ranging from equipment malfunctions to unexpected collisions are systematically identified and mitigated. As AUVs take on increasingly complex tasks, such as deepwater pipeline inspections or near-platform work, operators must demonstrate full compliance with these standards, including protocols for emergency shutdowns, redundancy systems, and fail-safe mechanisms designed to prevent harm to personnel, the environment, or critical infrastructure [73].

Additionally, the move toward higher degrees of autonomy raises questions about collision avoidance, liability, and operational accountability. When AUVs make decisions independently whether related to navigation or anomaly detection there is a need for clear guidelines outlining how and when human supervisors may override those decisions, as well as protocols for assigning responsibility if accidents occur. This transitional period calls for regulatory bodies and industry stakeholders to collaborate on updating or introducing frameworks that accommodate the nuances of autonomous subsea operations. In practice, achieving this alignment between technology capabilities and regulatory expectations is essential for fostering innovation while maintaining the high safety and environmental standards demanded by the offshore sector [74].

4.6. Cost-Benefit Analysis

Despite the potential for long-term cost reductions through minimized vessel requirements, fewer personnel, and lower risk of catastrophic failures, the initial capital outlay for acquiring and deploying advanced AUVs remains a substantial hurdle for many stakeholders. High-performance vehicles especially those equipped with cutting-edge sensor suites, robust autonomy features, or resident (seafloor-dwelling) capabilities often come with steep price tags [75]. In addition, operators may need to invest in specialized support systems, such as docking stations or data processing platforms, compounding the financial commitment. While these expenditures can eventually pay for themselves through more efficient inspections and avoidance of expensive operational downtimes, the near-term cost may be difficult to justify, particularly for smaller or mid-sized companies with limited budgets.

Moreover, organizational adoption of AUV technology can incur indirect costs, ranging from workforce training to workflow integration and technology support. Organizations accustomed to traditional ROV or diver-based methods may need new skill sets such as data analytics or AI algorithm development to fully leverage the AUV's inspection outputs. Larger multinational corporations typically possess the resources and risk tolerance to trial and gradually scale up innovative approaches. In contrast, smaller operators can be more cost-sensitive, facing tighter profit margins and greater aversion to large capital expenditures [76]. Consequently, the overall economic viability of AUV adoption is influenced not only by technology performance but also by the operator's scale, strategic objectives, and capacity to manage initial financial hurdles in pursuit of long-term gains.

5. Future Outlook and Research Directions

AUVs are on track to become even more integral to offshore operations as artificial intelligence and machine learning methods advance. By leveraging deeper neural networks for both sonar and optical interpretation, AUVs can detect anomalies more rapidly and with higher accuracy, cutting down on time-consuming post-mission data processing. Adaptive mission-planning algorithms will also benefit from AI improvements, enabling vehicles to adjust their routes in real time based on immediate observations, operational demands, or changing environmental conditions [77,78].

In tandem with smarter data interpretation, the concept of subsea residency stands to revolutionize inspection strategies. By permanently stationing AUVs at underwater docking platforms, operators can quickly deploy vehicles for routine surveys or urgent interventions, shortening response times and reducing the reliance on large support vessels. Advanced charging solutions at these docking points and high-bandwidth data links will further extend AUV operational reach; while evolving technologies such as autonomous intervention widen the scope of AUV tasks to include basic maintenance and repai [79]. Meanwhile, the emergence of swarm robotics where multiple smaller AUVs collaborate could facilitate faster, more robust data collection over vast areas, building redundancy into mission-critical operations.

Looking ahead, continued development of new energy systems including fuel cells and high-density batteries will underpin longer missions with heavier sensor payloads, supporting more frequent and comprehensive inspections. However, fully realizing the potential of AUVs will hinge on standardization and collaboration across the industry. Unified technology platforms shared best practices, and research partnerships among oil and gas operators, subsea service providers, and academic institutions can drive down costs, expedite technology maturity, and foster regulatory acceptance [80]. Collectively, these advancements promise to enhance operational efficiency, safety, and environmental stewardship in the challenging waters where modern offshore projects take shape.

6. Conclusion

The evolution of Autonomous Underwater Vehicles for inspection and loss prevention marks a significant turning point in subsea operations. By offering enhanced data collection, cost savings, and safer working conditions, AUVs have become indispensable tools for offshore asset integrity management. While challenges related to navigation accuracy, energy constraints, and regulatory standards persist, continuous advancements in sensor technology, AI-driven autonomy, and subsea residency concepts promise to further boost AUV adoption and operational efficacy.

As the industry increasingly aims to automate subsea processes, AUVs stand at the forefront of technological innovation in deepwater environments. Future developments in areas such as fuel cell power systems, advanced perception algorithms, and robotic intervention capabilities will broaden the scope of tasks AUVs can undertake, moving from pure inspection to comprehensive asset maintenance. Ultimately, these advancements will help ensure safer, more reliable, and environmentally responsible exploration and production in the offshore oil and gas sector.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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