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A Review on the Advances in Underwater Inspection of Subsea Infrastructure: Tools, Technologies, and Applications

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Abstract: *Subsea infrastructure is seen to be of extreme importance in facilitating offshore energy generation, telecommunication, undersea defense, and environmental monitoring systems. Currently, the number of offshore and underwater installations used by the whole world is on the rise, which is why the need to find as efficient and reliable approaches to inspection as possible is on the rise. Conventional diver-based inspection methods fall short in depth, safety and scale. This paper has examined the existing challenges in subsea inspection and discussed the advantages as well as disadvantages of Remotely Operated Vehicles (ROVs), Autonomous Underwater Vehicles (AUVs), and semi-autonomous ROVs in multiple inspection conditions This paper has presented rather advanced tools like advanced sonar systems, Autonomous Underwater Vehicle (AUVs), integrated survey platforms, and artificial intelligence (AI)-based analytics. This paper also examines in detail these technological advancements mainly their principles, applications and effectiveness. It also addresses issues related to submerged environment and future of subsea inspection.*

Keywords*: Subsea, AI, technologies, AUVs and Advance Sonar systems (ASS)*

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1.0 Introduction

A wide and highly connected system of pipelines, risers, subsea production systems, telecommunication cables, and renewable energy foundations make up a subsea infrastructure. They are applied in harsh underwater settings, which causes them to be under constant threat of corrosion, mechanical stress, biofouling as well as sediment deposition. Considering the severe regime of operation, the typical inspection becomes crucial to preserve structural integrity, guarantee the reliability of operation, and prevent the occurrence of devastating failures. In the past, under water inspection was carried out manually by the use of divers. But all these initial methods were limited with poor visibility, limited diver stamina and great safety risks. The development of Remotely Operated Vehicles (ROVs) took a great change and led to an extension of the depth and time of inspection observances through a smaller engagement of direct human interaction. Clearly, ROVs were, however, limited by the problem of tethering and the need of the skilled operators in spite of their enhancement (Marani *et al*., 2009).

The current trends caused a paradigm shift in the inspection of subsea infrastructure, which is mostly caused by the needs of the offshore oil and gas industry and the rising usage of automation. The Autonomous Underwater Vehicles (AUVs) became a disruptive technology, which provides untethered operation, and an increase in autonomy in the navigation system. Current methods that operate on these systems include the application of advanced sonar imaging, optical sensing modules and embedded data fusion methods, which greatly enhances the precision and depth of subsea checkups (Williams & Groen, 2012). In addition, the active involvement of innovative technologies, machine learning (ML), artificial intelligence (AI) and real-time analytics has disrupted the inspections process. New generations of robotic platforms have high-resolution sensors and onboard computing capacity that enables free discovery of anomalies, evaluation of defects, and execution of repair activities. Such transition facilitates the transition of reactive maintenance techniques to proactive and predictive approaches to the management of the infrastructure (Yoerger *et al*., 2007; Gomes *et al*., 2016).

Regardless of the remarkable innovation made in the field of subsea inspection, there are still quite a number of issues that foil ideal operations. The subsea environment is usually characterized by highly turbid water with very poor visibility that makes the way sensors work to be inaccurate. The obstacles in navigation control are autonomous navigation, and accurate localization in flowing currents and uneven seafloors. The difficulty of inspection on the one hand are the sensor degradation by biofouling and corrosion and the volumes of data being generated that in many instances overwhelm onboard processing capabilities. Also, the challenge of incorporating a wide range of platforms and technologies into a cohesive system is both technical and logistic. Under water inspection, pipeline inspection and their good installation and sub-sea inspection with the help of advanced vehicles assist in construction, operation, maintenance and repairs in deep water have been reviewed in this paper. The proposed investigation is expected to critically assess the existing tools and technologies of the inspection such as sonar systems, AUVs, integrated platforms, and AI/ML solutions with an aim of suggesting the future research directions needed to resolve the existing challenges.

Platform inspection: Offshore platforms should always be carefully and regularly inspected so that the integrity of the structures and safety of the installations could be ensured. Those checks usually concentrate at perusing structural conditions like corrosion signs, mechanical strains and material strains. Due to regular monitoring, the early-stage degradation can be identified which may affect the safety of use or create costly repairs in case it is not noted in advance (Tangirala, 2011; Mai *et al*., 2016). What is more, modern strategies tend to use robotics and sensor instrumented systems to make such inspections more accurate and efficient (Chitre *et al*., 2008).

Sub-sea installations: There is a global rising trend of the use of sub-sea installations rather than the use of the traditional surface infrastructure. These changes are heavily fueled by financial benefits that can be realized at the deep-water environments where topside structures are costly and difficult to operate. Also, easing the position of the equipment nearer to the wells of production boosts the productivity of the activity and minimizes the loss of energy. Fig. 1 represents the worldwide financial impacts ensuing in putting up of sub-sea infrastructure. With the increased spread of such installations, the need to perform regular checkups, examinations, and repair becomes larger, thus driving the market of Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs) (Mai *et al*., 2016; Pålsson *et al*., 2014).

Sub-sea pipelines and cables: A large part of the sub-sea vehicle uses is in inspecting sub-sea pipelines and cables. They are usually stretched to long lengths along the seabed thus making them unique as opposed to fixed structures. The inspection is normally made possible by vehicles that have a constant altitude, usually few meters, over the pipeline or cable in order to provide consistency in imaging, as well as, data accuracy. Accuracy must also be very high so as to avoid inaccurate data due to the movement of the vehicle (Evans *et al*., 2009). It is believed that the utilization of AUVs will provide less-costly alternatives and enhance the quality of obtained data (Evans *et al*., 2009; Donald, 2012).

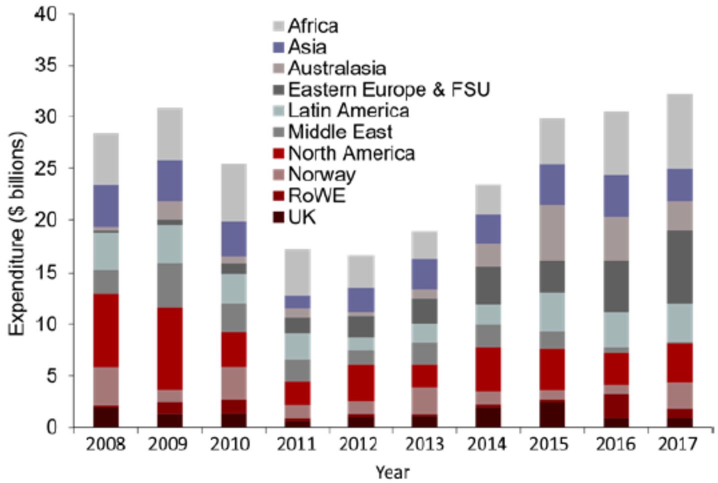

Fig. 1: Estimated global investment trends in sub-sea installations, highlighting associated capital expenditures (Mai *et al*., 2016)

In addition to that, these mobile systems can be used as a sure way to confirm knowledge found in surveillance systems running 24 hours a day as in fiber-optic systems and acoustic methods (Mai *et al*., 2016; Jalving *et al*., 2003).

Remotely operated vehicles (ROVs): Underwater Remotely Operated Vehicle (ROV, Fig. 2) is a remote-controlled vessel operating underwater and is piloted by a control post usually on a floating vessel or offshore facility (Waldner and Sadhu, 2024). These vehicles are attached with the operators through an umbilical tether that can enable real time transmission of the control commands and the video feedback. The tether does not only provide power to ROV but it is also a mechanical connection which can be utilized to pull the vehicle in case of need. Such systems are commonly used in underwater/subsea sectors to perform activities like inspection, maintenance, and data collection in other hazardous or inaccessible environments of human's divers (Mai *et al*., 2016; Yuh, 2000).

Autonomous underwater vehicles (AUVs): An Autonomous Underwater Vehicle (AUV; Fig. 2) is similar to an ROV except that a human operator is not actively and continually involved once the device has been deployed. The vehicles move under the route of pre-determined mission plans and have the flexibility of going out and performing inspection or data gathering independently (Waldner and Sadhu, 2024). AUVs are also installed with onboard intelligence, sensors and propulsion to be able to perform various operations which include seafloor mapping, infrastructure inspection and environmental monitoring. They remain especially useful when long-duration missions and activities are held or in regions of restricted access or difficult terrain since unlike their surface counterparts they are not prone to outside control (Mai *et al*., 2016; Jalving *et al*., 2003). Due to progress in technology, AUVs are becoming equipped with artificial intelligence and machine learning algorithms to be able to make better decisions in the dynamic underwater scenario (Paull *et al*., 2014).

2.0 Technological framework for subsea instrumentation and data collection processes

Remotely operated underwater vehicles, and Autonomous underwater vehicles are usually armed with different onboard sensors during the inspection of subsea infrastructure; their objective is to gather information of the surroundings and structure. These sensors make use of various fields of imaging and measurement technologies to evaluate the well-being of subsea assets. Most of these systems create two-dimensional (2D) or three-dimensional (3D) spatial-temporal data which is useful to create dense visualisations of the structures and environments surveyed. As it is explained by Mai *et al*. (2016) and Waldner and Sadhu (2024), such sensing systems may be divided into various main types according to the way they operate and the type of data they obtain.

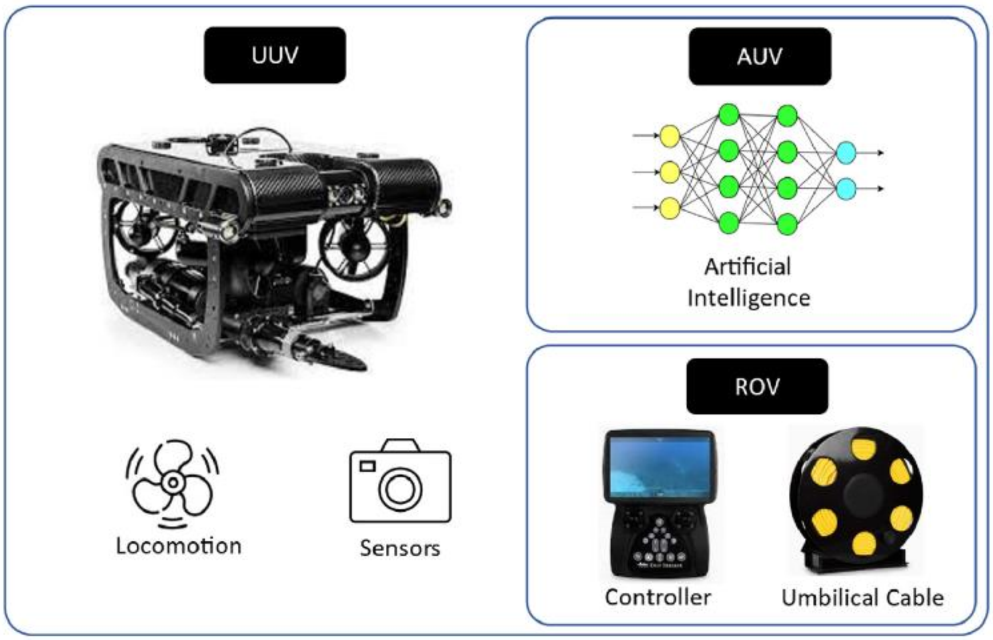

Fig. 2. Conceptual relationship among Unmanned Underwater Vehicles (UUVs), AUVs and ROV (Waldner and Sadhu, 2024).

2.1 Optical and visual Imaging systems

Optical inspection is still one of the most fundamental ways to study the underwater area and is typically being offered on almost any type of underwater vehicle. Such systems normally comprise of digital video cameras that offer analog sensitive or high-definition digital feeds. In a more sophisticated and larger ROV, the transmission of high-res video is performed by using fiber-optic cables whilst over-coming the shortcomings of the older coaxial unit. The main purpose of visual systems with ROVs is to provide the operator with guidance in the course of navigation as well as the close inspection. Visually, AUVs on the other hand use visual details as inputs to position themselves during autonomous operations, which may be further complemented with computer vision methods like Simultaneous Localization and Mapping (SLAM) that enables the vehicle to self-locate independently of the operator (Mai *et al*., 2016; Waldner Sadhu, 2024). The visual tools also play an important role in detecting the surface defects, marine growth and mechanical damages (Waldner & Sadhu, 2024).

Acoustic imaging: Sonars and Echosounders

A major component of underwater inspection systems is acoustic sensing instruments, and sonars and echo-sounders in particular (Fig. 3). The sensors create acoustic images of the sea floor and this enables detecting details that include sediment deposits, debris beds, structural defects, and pipeline motion. Sonar systems have the ability of sweeping in front of the vehicle or beneath it and depending on the configuration used creates a very broad coverage of the area in question. The most common include multibeam sonars (Fig. 3) and side-scan sonars, which are capable of providing resolutions and scanning patterns that are customized to missions (Mai *et al*., 2016). Figure 3 indicates a general sonar installation and its imaging results. Sonar has the particular advantage in turbid or low-light conditions in which optical methods are ineffective (Mai *et al*., 2016; Fig. 3).

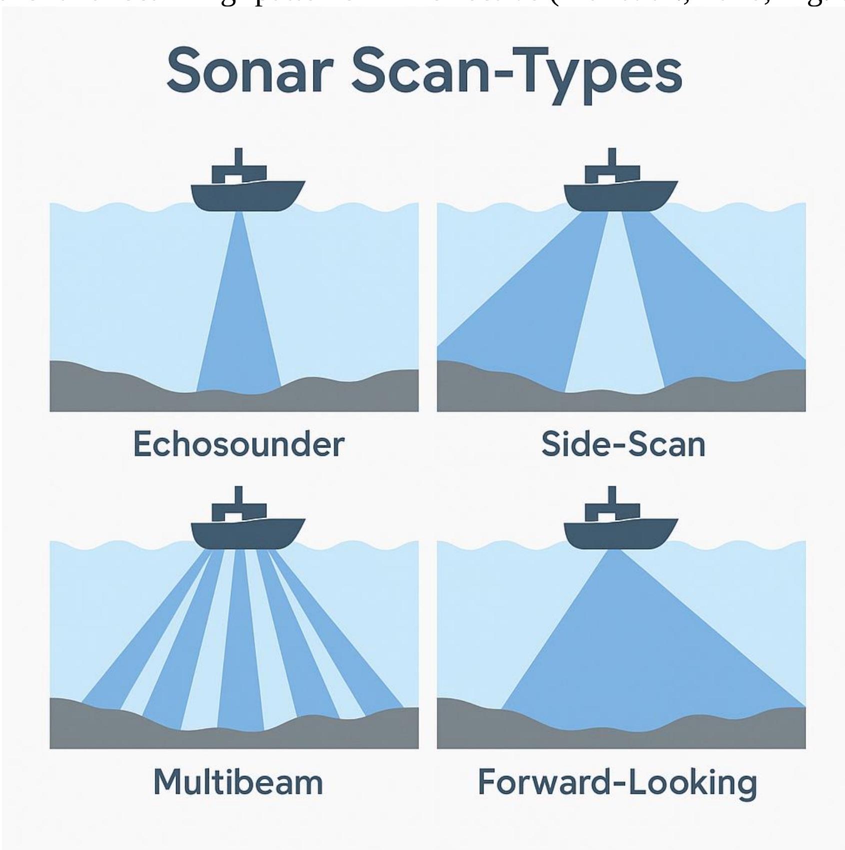

Fig. 3: illustrates four common sonar scanning methods used in underwater survey (Modified after Paull *et al*., 2014)

2.2 Magnetometric survey systems

Changes in the secondary magnetic field that will respond to a change in the structure of the object under examination, pipes in this case, are measured using magnetometric sensors. Such differences can serve as signs of corrosion or thinning of the walls or internal flaws. These sensors give a side view representation of data by examining magnetic anomalies, thus reinforcing the visual and sonar based data. Such non-destructive testing method is beneficial in locating internal flaws, which otherwise would have remained hidden to optical as well as acoustic detectors (Waldner & Sadhu, 2024).

2.3 Imaging Laser-based scanning

Subsea Laser scanning methods, including Light Detection and Ranging (LiDAR) are becoming common although it is impeded by the significant optical attenuation caused by water. Such systems are capable of capturing 3 D, high resolution data of the subsea infrastructure, comparable in performance to multibeam sonar (Fig. 3) and with minutia of the surface in clear water conditions. However, the main disadvantage of underwater laser technology is its narrow working scope in terms of its operating field because the light inside the seawater has been consumed, which means that it is not as effective as the laser on earth or air (Mai *et al*., 2016). However, when water clarity is possible, LiDAR will produce accurate digital images which can be used in fine-scale structural evaluation (Beltrn *et al*., 2021).

3.0 Smart data management and autonomous operation in marine and underwater surveying technologies

The fast development of robotics and IT technologies has given the sphere of data collecting, manipulating, and presentation underwater a totally different outlook, especially as applied to Remotely Operated Since in submersions, and Autonomous Underwater vehicles (AUV). There is an upswing in the application of user-interactive and improved data representation techniques, such as real-time 3D visualization coupled with traditional capabilities such as time-series graphs, position tracking and orientation displays (Mia *et al*., 2016; McCann, 2002). The operators in modern systems can visualize the heading and the position of the ROV, in a simulated 3D environment, and, at the same time, view pertinent environmental parameters, video input, sampling activities and notes. This is a multi-layered interface that allows learning everything about underwater environments. Commercial software platforms are still advancing in visualization ability, particularly, at the direction of high resolution and 3D scanning imaging (Donald 2012). Such upgrades help in better data collection but lead to too much data which definitely and clearly requires good post-processing mechanisms to process and analyze the information.

Methods of visual inspection have also changed. As an example, Ridao *et al*. (2010) used image mosaicking procedure with vehicle-based sensors as well as image feature extractions to develop complete visual maps of underwater structures. These tools make very useful visual datasets by patching numerous frames of images into a non-disparaging and hierarchical interface. On the physical and computing front, highly compact, low power consuming electronics has enabled the possibility of provisioning the ROVs to be more autonomous without necessarily expanding the costs of operations. These improvements allow a widespread of automatic control services, both simple pilot-assistance tools to sophisticated mission planning algorithms. The degrees of autonomy possible in both ROV and AUV systems are usually depicted in Table 1 as represented by the introduction of more degrees of autonomy as the design evolves to a greater level.

Table 1: Operational modes of subsea vehicles with descriptions, applications, and sensor requirements (Tena, 2011)

Mode	Description	uses	Sensors	Optional
Station-keeping	Keep stationary	Inspection and intervention	AHRS, Depth, Velocity	Absolute position using acoustic means
Cruise-control	Keep constant velocity vector	Pipeline and cable inspection, good for surveysensors	AHRS, Depth, Velocity	Survey sensors
Survey control	Follow a set of predetermined way-points	Route and pre-lay surveys,	AHRS, Depth, Velocity,	

		good for survey-sensors	Acoustic Beacons
Survey-tracking	Follow a structure (pipeline or cable) using (multibeam) target sensors	Touch-down monitoring, inspection, intervention.	AHRS, Depth, Velocity, Acoustic Beacons, Target sensors

Control systems in research are commonly categorized into low-level control, such as position, and attitude controller and high-level mission planning, whereas numerous commercial systems provide capabilities such as station keeping and cruise control, to help the operators in conditions of demanding environment (Whitcomb, 2000). Less complex tasks, however (e.g. waypoint navigation, numbered task execution sequencing) have not yet been deployed in real-world activities, mainly because of the latencies caused by top-side control structures.

The trend in the recent past has been to attain higher autonomy in the undertakings of subsea tasks. As an example, autonomous underwater monitors and inspection have been suggested by persistent AUVs that would allow vehicles to permanently stay submerged and be prepared to autonomously conduct missions when requested (Mia *et al*., 2016; Kim & Kim, 2019). The intention of these vehicles is to map high-resolution, textured 3D models of underwater property, pipes as well as valves. They will use new navigational procedures, which employ directional structure of underwater installations to navigate precisely. Beyond that, the reduction of human dependency, making it dynamic to uncertain environmental situations and allocating independent functions such as inspection, cleaning, and mechanical work, such as turning the valves is the goal (Mia *et al*., 2016). This is the direction to the full autonomous systems that can be able to conduct complex underwater missions with the smallest supervision at the surface level. These developments have been enabled by parallel progress in underwater sensor technologies and artificial intelligence or embedded computing systems that between them appear likely to deliver a future where inspection and maintenance of systems deep underwater and at minimal risk can be carried out with great precision (Christ & Wernli, 2011).

3.0 Artificial intelligence and machine learning in underwater surveying

Machine Learning (ML) and Artificial Intelligence (AI) entered the stage of revolutionizing the interdisciplinary sectors by offering reliable answers to the problems of data interpretation, real-time decision-making, and self- navigating (Ufomba & Ndibe, 2023; Ademilua & Areghan, 2025a; Ndibe 2024; Adjei, 2025a; Igbinenikaro *et al*., 2024; Alahira *et al*., 2024; Adjei, 2025b ; Abolade, 2023; Ademilua & Areghan, 2022; Dada *et al*., 2024: Adjei, 2025c; Abolade, 2023; Ademilua & Areghan, 2025b; Utomi *et al*., 2024; Ndibe; 2025a; 2025b; Okolo *et al*., 2025). The complexity of the current tasks being performed underwater and a high requirement of clear and timely information have placed AI and ML as the necessary tools in the field. In this section, the substantial impact of AI and ML technologies on underwater surveying, current use of this area, and the potential development will be considered. AI and ML solutions are very efficient in handling large volumes of data that is gathered by the latest underwater technologies such as sonars, multi-spectral imaging and optical sensors. Such complex data are usually not addressed well by the traditional techniques of analysis. Nevertheless, clever algorithms will be able to process these amounts quickly and receive timely judgments of underwater conditions and irregularities (Adeoye *et al*., 2024; Nwokediegwu *et al*., 2024). As another example, visual data recorded underwater cameras can be interpreted by AI models to identify particular features, including coral reefs, irregularities of the sea bottom, the subsea facilities, and sea creatures, to increase the effectiveness of both environmental monitoring and infrastructure evaluation (Fiorentino *et al*., 2021).

The application of AI and ML in autonomous underwater vehicles (AUVs) is an improvement in the subsea exploration. The presence of these algorithms enables AUVs to accomplish complicated tasks on their own and still be able to adapt their navigation routes to any altering environmental factors. The combination of AI and AUVs allows interpreting sensor data on the fly and adjusting operations based on it without any direct human intervention (Aderibigbe *et al*., 2023; Etukudoh *et al*., 2024). Moreover, these vehicles can recognize and classify objects (pipelines, wrecks, ecological habitats, etc.) present underwater and classified with high precision by using the AI to recognize objects.

Among the important advantages of the use of AI in the subsea environment is the optimization of missions plans. ML algorithms could decide the most efficient route of AUVs; this would enable AUVs to move away without facing obstacles and covering as much as possible the area to survey. It does not only minimize the use of fuel and the battery but also enhances data quality and volume retrieved (Adeleke *et al*., 2024; Ohalete, 2022). Also, the sensor fusion driven by AI can be used to combine data obtained by different sensors, including acoustic, optical, and inertial, into some coherent 3D surfaces thereby enhancing the reliability and spatial precision of the underwater mapping activities (Paull *et al*., 2014). As technology moves forward, an expanded AI and ML functionality will be the main driver towards increasing autonomy and intelligence in underwater vehicles. Such advancements will enable further investigation, extended mission, and elegant data decoding into dynamic seas. In prospect, the integration with the most recent types of sensors, including hyperspectral imaging and high-frequency acoustic arrays, that have the potential of providing highly precise granularity of data on collected information, could also be involved (Abatan *et al*., 2024; Sonko *et al*., 2024). Such advances will become essential in fields like into environmental monitoring, offshore oil/gas projects, maritime archaeology, and climate change research.

Real-time surveillance and anomaly detection is also possible in real-time through AI during subsea operation. It plays a crucial role in making interventions in good time in cases of emergency such as leakage of oil or breakage of the structure of underwater installations. Such predictive modeling based on ML is also extremely useful when it comes to predicting the changes in marine life, sediment transport, and water quality in providing proactive solutions to conserving and managing coastal environments (Atadoga *et al*., 2024; Ohalete *et al*., 2023). These models can be used to predict trends, such that the stakeholders would use evidence-based decisions when dealing with natural and engineered aquatic systems. AI-driven systems have the ability to reduce the cost and the accuracy of subsea surveys drastically as these tedious and labour-intensive processes are automated. This causes massive efficiency increments, through the reduction of human error, the streamlining of the operations and allowing an analysis of the data generated by various sources simultaneously (Nwokediegwu *et al*., 2024; Sodiya *et al*., 2024). One other thing that the AI-powered monitoring systems enable is taking the constant view of the underwater environments which is particularly crucial to long-term environmental research activities and in real time intervention especially in areas prone to disasters (Umoren *et al*., 2025). In conclusion the use of AI and ML in underwater surveying is transforming the process of exploring the underwater environment and the capacity to comprehend it. Such innovations have leveled up the functions of underwater vehicles, data processing, and accuracy of the ecological and structural assessments (Ugwuanyi *et al*., 2024; Usman *et al*., 2024). Through continuous research and development, interdisciplinary cooperation, AI, and ML will open up further levels of functionality that will make exploration of the ocean depth smarter, safer, and more efficient.

4.1 Challenges and future direction

In spite of the great advancements in the field of the subsea inspection technologies, there is still a number of issues which limit the widespread application of autonomous systems and their operation. Among the most prominent concerns is sensor restriction: optical sensors tend to be ineffective in hard or low-visibility spaces, whereas acoustic systems, although much more accurate in those settings, have limitations based on resolution and noise obstruction. Another important issue of interest is energy consumption and in particular, long-duration or deep-sea missions, where the current AUV battery technology can in many cases not cope with the task at hand. There is also the limitation imposed by underwater acoustic bandwidth inherent of underwater communication that limits the capability of real time data transfer and remote controls. There is also the data overload issue whereby the huge amount of data acquired in subsea survey needs to be filtered, compressed and intelligently analyzed to retrieve relevant information. Adding to this already complex operating environment is non-standardization of platform and data formats that extends compatibility problems, makes collaborative projects troublesome and causes a low efficiency in multi-system integration.

In the future, a few novel initiatives would overcome these obstacles and redefine the future of subsea surveys and infrastructure surveillance. Among these developments is the adoption of swarm robotics, whereby large regions are covered in a flexible and efficient way by fleets of AUVs operating in cooperation. Another trend is a bio-inspired vehicle design, which has an improved capacity of hydrodynamics and mobility due to being based on the efficient movement of aquatic organisms. The edge computing onboard is gaining more and more importance, which means that AI algorithms will be calculated locally on the vehicle, and not all data have to be transmitted in large bulk, but faster decisions can be made.

Another promising avenue is the introduction of digital twin technology whereby data on inspection on assets may be fed in real time to virtual replicas of the subsea structures, enabling the operator to simulate, observe, and forecast the behaviour of the asset. In addition, using improved sensor fusion of sonar, LiDAR and optical imaging data should be able to offer a better and more thorough impression of the underwater environment. Collectively, these innovations are indicating at the future of smart and efficient and autonomous underwater inspection systems, which can help to establish resilient and sustainable offshore operations.

5.0 Conclusion

The study carry-out a concise review on the advances in underwater inspection of subsea infrastructure, technologies, and applications. Remotely Operated Vehicles (ROV) subsea inspection is not new and many operators and manufacturers have long experience in using visual, acoustic, and other non-destructive testing methodologies. Traditional equipment like, magnetometric, ultrasonic, along with cathodic protection inspection systems, have been effective for subsea assets assessment. Those techniques remain imperative in the scope of offshore maintenance, which, however, is supplanted by growing innovations of automation and sensor integration targeting enhanced efficiency and mitigating the risk of operation.

The recent developments of robotization, sensorics and artificial intelligence have created a new age of subsea inspection. The ability of the underwater vehicles to move beyond the diver controlled and manually operated to intelligent selectively and all-controlled systems, especially Autonomous Underwater Vehicles (AUVs) has greatly enhanced data retrieval, safety, and speed of operations. Improvements in both visualization tools and post processing applications have also facilitated inspection outputs to be more accessible and consumed by the end-user so that decisions can be based on detailed information more readily.

Although these have been great technological steps towards autonomous solutions, the offshore industry has been conservative in embracing full autonomous solutions. Difficulty of usage, unreliability in tough conditions and economical constraints have hampered large scale usage. According to players in the industry, when it comes to large financial interests, the decision-makers prefer going with established techniques and methodologies, instead of new technologies, despite the possible advantages. In addition, the systems are yet to be integrated with rigorous testing, data interpretation models and trust in operations controlled by machine.

A synergistic combination of smart robotics, AI and real-time sensor feedback heralds a paradigm shift in the management of offshore infrastructure. Inspection of crucial subsea assets becomes more and more possible under the condition of autonomous systems with predictive analytics that help to lessen human intrusion, which diminishes the cost of inspections and enhances resilience. The further investment in the research and innovation is as vital as progressive targeting of the present limitations itself and the realization of the scalable, sustainable, and intelligent programs of monitoring in the complex underwater conditions.

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