Applications of robotics in floating offshore wind farm operations and maintenance: Literature review and trends

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REVIEW ARTICLE

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Applications of robotics in floating offshore wind farm operations and maintenance: Literature review and trends

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Abstract

Marine operations required to transfer technicians and equipment represent a significant proportion of the total cost of offshore wind. The profile of sites being considered for floating offshore wind farms (FOWFs), e.g., further from the shore and in harsher environments, indicates that these costs need to be assessed by taking into account the maintenance requirements and restricted weather windows. There is an immediate need to investigate the potential use of robotic systems in the wind farm's operations and maintenance (O&M) activities, to reduce the need for costly manned visits. The use of robotic systems can be critical, not only to replace repetitive activities and bring down the levelised cost of energy but also to reduce the health and safety risks by supporting human operators in performing the desired inspections. This paper provides a review of the state of the art in the applications of robotics for O&M of FOWFs. Emerging technology trends and associated challenges and opportunities are highlighted, followed by an outline of the agenda for future research in this domain.

KEYWORDS

autonomy, floating offshore wind farm, operations and maintenance, robotics

1 | INTRODUCTION

The deployment of floating offshore wind turbines is gaining traction as their potential installation locations provide the opportunity to exploit stronger winds and larger farm sizes, while also reducing the prevailing conflicts of interests with other factors such as societal acceptance and

List of abbreviations: FOWF, floating offshore wind farm; O&M, operations and maintenance; BoP, balance of plant; UAV, unmanned aerial vehicle; VLOS, visual line of sight; BVLOS, beyond visual line of sight; ROV, remotely operated vehicle; AUV, autonomous underwater vehicle; ASV, autonomous surface vessel; CTV, crew transfer vessel; SOV, service operations vessel; CAPEX, capital expenditure; OPEX, operational expenditure; LCOE, levelized cost of energy; H&S, health and safety; NDT, non-destructive testing; TRL, technology readiness level.

visual impact.[1] However, maintaining floating offshore wind farms (FOWFs) to allow them to perform at their optimal level for over 25 years of service can account for 29.5% of the total lifecycle cost.[2] It has been estimated that the operations and maintenance (O&M) of onshore wind turbines account for about 25–30% of the total lifecycle cost of wind turbines, and in the case of offshore turbines, the costs are even higher, in the range of 30–35%.[2,3]

The O&M activities for FOWFs involve inspecting and maintaining components of the wind turbines and their subsystems to prevent and address faults. O&M activities on the turbine blades are typically performed by rope-access technicians, often working in extreme conditions and during restricted weather windows. The duration of turbine downtime and hence the lost energy production can be considerable, while the use of crew transfer vessels (CTVs) and service operation vessels (SOVs) also makes up a significant proportion of the wind farm O&M costs.[4] The O&M of FOWFs poses significant technological and economical challenges pertaining to asset downtime, operational expenditure (OPEX) incurred, data quality, and fault diagnosis and prognosis.

Recent advances in the development of offshore robotics have opened up new opportunities for deploying semi or fully autonomous systems for the O&M of offshore wind farms.[5] Incorporating robotic systems offshore can not only improve the assets' reliability but could also reduce costs and mitigate the health and safety (H&S) risks associated with deploying human operators to offshore sites with harsh weather conditions. In recent years, a host of new projects has focused on the autonomous inspection and maintenance of offshore wind turbines.[5,6]

This review paper gives an overview of the state-of-the-art in the application of robotics-based O&M for FOWFs with the objectives of the following:

1. Identifying O&M tasks that could be performed or supported by the robots.
2. Determining the technical feasibility of incorporating different types of robots in the FOWF environment.
3. Discussing challenges and future trends to make the robotics-based O&M commercially viable.

The paper is structured as follows: Section 2 gives an overview of the O&M activities associated with FOWFs. Section 3 presents the applications of robotics for conducting O&M and an overview on the existing use-cases. Four robotic systems are presented here, namely, climbing robots, aerial robots, subsea robots, and autonomous vessels. In Section 4, potential areas of future research are presented and segmented into future robotic systems, design, and market challenges. This is followed by the conclusion in Section 5.

2 | OPERATIONS AND MAINTENANCE OF FLOATING OFFSHORE WIND FARM

In the wind power industry, the expression O&M is often used in reference to a broad set of activities including, but not limited to, administration, insurance, land leasing, civil works, and the wider asset management. In the context of this review paper, a slightly narrower definition is employed which pertains to activities associated with enhancing the performance and reliability of components and assets with an overall aim of increasing the production-based availability of FOWF. These activities include performing preventive and corrective maintenance, inspection, surveys, and conducting condition monitoring of various components and assets. Such activities are typically included in the scope of O&M contracts for wind farm operators[7] with an aim to maintain the asset following its installation and during its entire operational phase. The primary objectives of O&M are to ensure asset availability for smooth energy production and preserve equipment lifetime, while also taking into consideration the H&S aspects of the employees involved.

FOWF-specific O&M activities: Industry-wide studies[8,9] have identified different FOWF-specific O&M activities. It is pertinent to mention that the floating wind industry is still in its infancy, as compared with bottom-fixed, and these activities may be adapted as lessons are learned from more installations. These activities are associated with not only maintaining the wind turbine generator but also the floating platforms, mooring lines, anchors, and dynamic cables. For instance, annual surveys need to be conducted to inspect the condition of catenary moorings and drag anchors. Around once in every 5 years, moorings are raised to the surface for a detailed inspection. Furthermore, dynamic cables require regular visual inspection of bending stiffeners, transition joints, buoyancy modules, and marine growth. Floating platforms are designed to withstand weather conditions without failure for the duration of a turbine's lifetime; however, as with any other offshore structure, dynamic sea conditions may result in the occurrence of cracks. A number of factors exist that can affect the implementation strategies for O&M in the case of FOWFs. A few of them are summarized below:

1. *Limited accessibility and dependance on weather windows*: In order to reap the maximum benefits pertaining to energy generation, FOWFs are being deployed farther into the sea. The wind conditions at such locations are more suitable for higher and more consistent energy generation.[10] But this also brings about a host of challenges such as the difficulty to access the turbines for conducting preventive or corrective maintenance due to sparse availability of weather windows. The higher values of significant wave height at FOWF sites also constrain the O&M scheduling and logistics.

2. *Increased loads*: FOWF turbines are subjected to higher cyclic loads due to dynamic response of the turbine to wind and wave profiles. Hence, they are prone to more structural damage as compared to their onshore or bottom-fixed counterparts. The sub-systems such as foundation and mooring lines will also be subjected to harsher wave conditions which may have an effect on the individual component's lifecycle. Consequently, the inspection and maintenance activities need to be considered more often for these turbines.
3. *Resource constraints*: The resources needed to access FOWFs for conducting maintenance may be limited owing to further distances from the onshore facilities and depots. These include procuring and replacing spare components, and the vessel logistics of transporting them to the offshore sites within the available weather windows. Furthermore, harsher environmental conditions and the floating foundations make the tasks more complex and time-consuming that can be challenging and risky for the personnel involved.
4. *O&M costs*: While the fixed O&M cost of a FOWF can be predetermined, the variable costs associated with transferring personnel and equipment to the offshore sites are subjected to the availability of weather windows, the type and duration of repair, and the significant wave height. This brings about a corresponding increase in the costs associated with leasing of CTVs and SOVs. Furthermore, the risks associated with safety and well-being are higher at these locations, and as such, the insurance costs are dearer.[11] These factors culminate in an overall higher OPEX for the wind farm.

In case of a FOWF, the O&M activities can be divided into the three broader categories, namely, turbine, balance of plant (BoP), and the offshore logistics-related activities. The turbine includes the tower and the rotor-nacelle assembly, while the BoP constitutes the supporting structure needed to generate and export electricity from the turbine. The offshore logistics is an important aspect in a FOWF as there is a need to account for the transportation of equipment and personnel to offshore sites under restricted weather windows. These three categories are discussed in detail below.

2.1 | Turbine O&M

The O&M activities associated with the turbine are centered around the tower, rotor blades, and the nacelle along with its mechatronic components. With the increasing capacity of wind farms in locations farther into the sea, the loading cycles on turbine and its sub-systems are envisaged to increase. Hence, the components are prone to be deteriorated frequently due to wear, corrosion, and fatigue. Various research studies have focused on both designing robust and motion-compensated platforms to access offshore wind turbines, and optimizing the scheduling and planning of maintenance activities, in order to maximise turbine availability and reduce costs.[12] In general, maintenance is defined to be either proactive or reactive in nature. The former relates to the preventive maintenance that is performed to mitigate the occurrence of a component or system failure in the future. Reactive or corrective maintenance is based on the repairing or replacement of a component or system when the damage, fault, or failure has already occurred. These can further be categorized as follows:

1. Preventive maintenance:

a. Calendar based: a fixed number of inspections or repairs per a specified interval of time, conducted by the operator irrespective of the damage state of the components or system.
b. Condition based: a repair or replacement is conducted based on the observed health of the component or system.

2. Corrective maintenance:

a. Deferred: when a failure is expected to happen, and the maintenance is planned and conducted in advance of the failure occurrence.
b. Immediate: when a failure occurs without any prior knowledge and the component or system needs to be put into idle mode or shut down for maintenance.

The prediction of faults before they occur through robust condition monitoring approaches can lead to significant reduction in the O&M costs. These approaches are based on analyses of specific measurements and aspects of operations such as fatigue analysis, strain measurement, thermal, and acoustic data. Recent advancements in sensors, data analytics, and the improvements in machine learning algorithms have opened-up new opportunities for integrated and in-depth system analytics, whereby different types of data can facilitate informed and reliable decision-making.

In FOWF conditions, the rotor blades and tower are continuously stressed by the environmental conditions, such as temperature changes and structural degradation. Example maintenance activities in this case include visual inspection for damage detection on lightning receptors, blade cleaning, and resident sensors' installation. The nacelle houses the drivetrain along with its components such as the gearbox. Although the advent of direct drive generators has mitigated the typical gearbox related faults, the need to continuously monitor the components is still required. Here, the aim is to predict the faults in due time so that the Mean-Time-To-Repair (MTTR) can be minimized. Next to this, the health of the tower needs to be monitored continuously in order to reduce the occurrence of worst-case scenarios. This is important as the floating platform is subjected to increased stochastic loads due to dynamic response of the turbine to wind and wave profiles, which results in structural fatigue. Another region is the splash zone; section of the turbine that is intermittently in or out of seawater during the turbine's lifecycle. This results in increased cyclic wave loading and hence, corrosion related effects are prone to occur especially in high wave conditions.[13] Based on a structural health monitoring system, such effects can be visually observed in advance, and repairs can be arranged before they become catastrophic failures.

2.2 | Balance-of-plant O&M

In the context of FOWF-specific O&M, the term BoP includes the activities of the wind farm that do not pertain to the wind turbine. These include inspecting the turbine substructure, laying out and maintenance of mooring lines and power export cables, conducting site surveys, and attaining metocean data. An illustration of these activities in the context of the entire FOWF is shown in Figure 1. In principle, the O&M strategy for wind turbine and BoP is executed similarly, but the maintenance processes are considered differently. The impacts on performance, costs, and reliability for a wind turbine system or component failure are more localized, in contrast to the BoP related failure. The latter can result in significantly reduced availability of the wind farm, along with a resultant increased cost of energy.[14] With the advent of larger wind farms in more remote offshore conditions, the maintenance of BoP systems is even more crucial for the effective operation of wind farm, and ensuring the export of generated power.

For large-scale FOWF applications, it is important to achieve maneuverability in a congested subsea space in order to deploy and inspect subsea structures such as mooring lines. Offshore regulations require subsea inspection at a minimum of every 2–5 years, depending on the specific system. Apart from that, new mooring lines and anchors may need to be procured and installed over time. Some industry figures indicate that one in every 100 mooring lines needs to be replaced in a year. On a farm of 100 turbines with four to five mooring lines each, this would mean between four and five mooring line replacements per year.[15] Finally, a robust maintenance strategy must be in place for emergency repair/replacement in response to worst case scenarios such as a mooring line breakage. Furthermore, geophysical and visual surveys need to be conducted after specific time intervals to comply with industrial and environmental standards.

2.3 | Logistics

In addition to the O&M activities related to the turbine and BoP, the transport of goods and personnel from onshore to the offshore sites and vice versa needs to be taken into account. Currently, most of these activities are based on CTVs which are used to transfer spare components, goods, and personnel to wind turbines and substations to perform both preventive and corrective maintenance. These are also utilized to perform asset protection and security operations for the wind farm. As the offshore developments are moving farther into the sea, SOVs are becoming increasingly relevant. In comparison to CTVs, they are larger in size and can carry heavier payloads along with staying at offshore locations for a longer duration of time. If larger or heavier components require installation or removal, then heavy lift vessels (HLVs), also known as jack-up vessels may be required. These are essentially crane barges that are towed to the desired site using tugboats. Jack-up vessels have higher day rates as

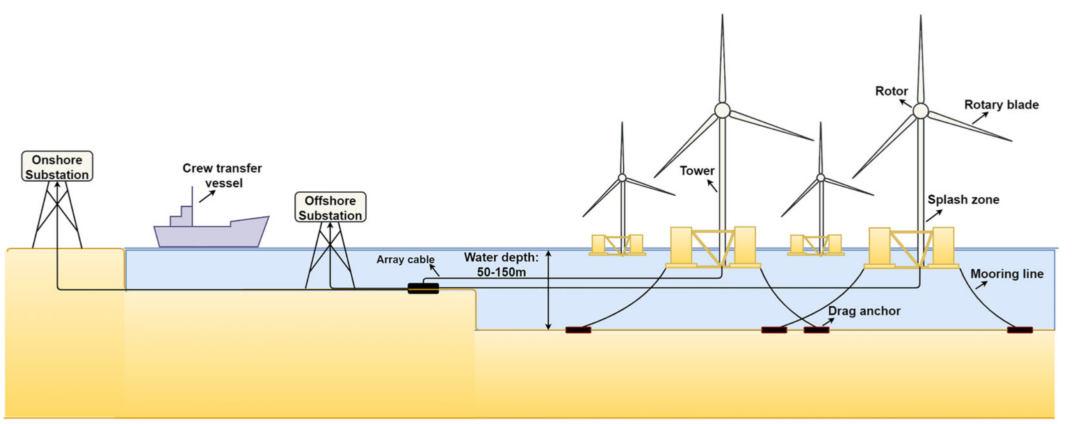

FIGURE 1 Illustration of a floating offshore wind farm with its typical sub-systems

compared to CTVs and SOVs, and are used for one-off charters to conduct corrective maintenance and repair of large components, e.g., turbine blades or generators. Recently, the use of helidecks is gaining traction on the offshore installations. These are mounted on turbines or the offshore vessels. The addition of offshore helidecks comes at higher financial expense but have benefits in terms of reducing transit times, providing greater accessibility, and complementing the vessel-based O&M activities.[16]

3 | ROBOTICS FOR O&M OF FOWF

A significant increase in the adoption of robotics in the oil and gas sector has been witnessed in recent years. This has been motivated by the advanced automation capabilities provided by the modern robots along with a reduction in the number of manhours needed in the rigs. This trend, obtained from GlobalData Patent Analytics,[17] is depicted in Figure 2, where the number of publications and patents granted over the past 20 years show rising interest for robotics in the oil and gas sector. This could provide with an approximation of the future growth in robotic systems in FOWFs and other marine renewables, as the O&M facets of the two domains are similar.

Robotic systems offer various opportunities to significantly change the nature of the offshore operations, ranging from efficiently executing the otherwise repetitive tasks to attaining continuous and high-resolution data. Furthermore, the potential financial advantages and H&S-related benefits for the personnel onboard at offshore installations necessitate the need to minimize the manual human intervention. In recent years, the concept of remote inspection in industrial processes has also been gaining traction, whereby unmanned aerial vehicles (UAVs) and remotely operated vehicles (ROVs) are being utilized to access the machines and sites that are otherwise difficult or dangerous for humans to operate in. Prototype systems have been developed and tested for fault detection in pipelines,[18,19] subsea survey and repairs,[20] and more recently for wind turbine inspections.[21]

To conduct this review and to gain a holistic overview of the trends related to the applications of robotics for offshore wind farms, articles were retrieved from Web of Science (Clarivate Analytics) using the key search terms “offshore,” “O&M,” “UAV,” and “ROV” and filtered by year (>2000), access, citations, and relevancy. In order to extract key trends, a network visualization of these papers was created which is shown in Figure 3. Furthermore, three distinct clusters were observed where majority of the publications were related to optimization of maintenance activities for offshore wind farms. This was followed by a cluster of fault detection, and condition monitoring based on SCADA. The third cluster was focused on the control system design of UAVs for acquisition and analysis of imagery data. A visualization of the robotics-based O&M for FOWF and the potential research gaps is shown in Figure 4. Apart from the key highlights, it was observed that more focus is being diverted towards costs, investments, data analytics, and proactive fault detection of turbine and its sub-systems. While the asset management and condition monitoring have been extensively studied, more recently, the applicability of remote inspection and big data management have started gaining attention. This elaborates that the trends have been moving towards devising innovative O&M solutions with an aim to achieve higher efficiency and safety while reducing the levelized cost of energy (LCOE). Although there are different types of robotic systems present, they all need to fulfill certain requirements in order to successfully complete their mission given the FOWF-related site constraints previously stated in Section 2. These requirements are as follows:

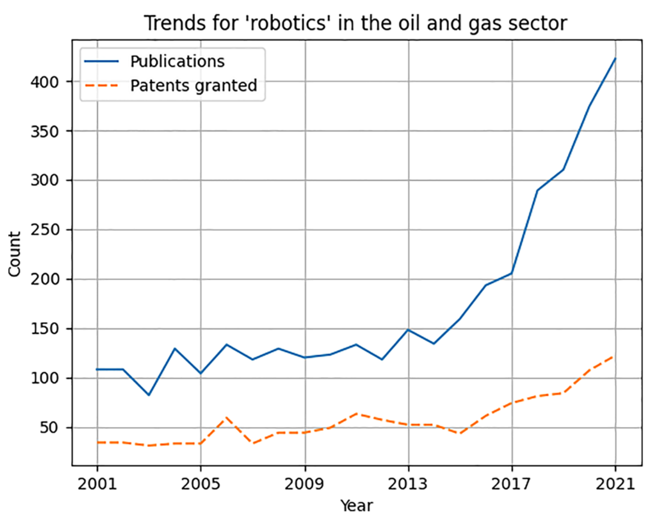

FIGURE 2 Number of publications and patents granted in the domain of robotics in the oil and gas sector[17]

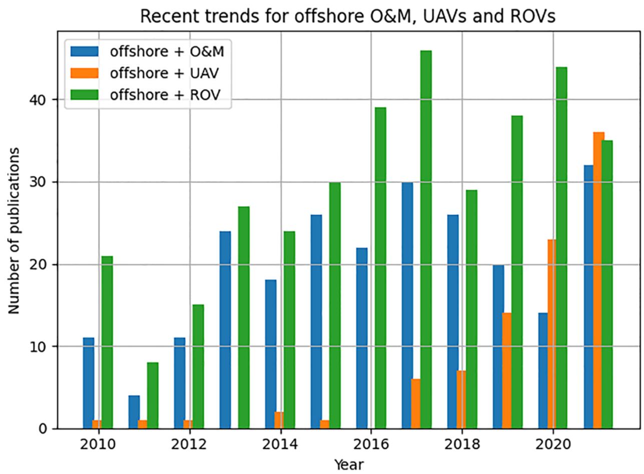

FIGURE 3 Publication trends of ROVs and UAVs for offshore O&M activities

FIGURE 4 Research pertaining to robotics for O&M. rectangular areas (grayed): widely investigated. Elliptical areas (with filled color): possible research gaps

- *Mobility*: Mobility pertains to the motion of the robot in unstructured environments under difficult operating conditions and at speeds that allow for efficient acquisition of inspection data. For instance, the thruster technology of a subsea robot should be reliable and controllable where it should be able to do the required task in an efficient manner while also minimizing the possibility of a crash into the asset. For subsea robots, the propulsive efficiency remains a challenge. This is highlighted by Phillips et al.[22] where it is shown that the subsea robots have to considerably increase their propulsive efficiency in order to navigate the waters like marine animals do. Simultaneously, the operational range of subsea robots also needs to increase for them to be useful for longer duration underwater monitoring activities. The design optimization on these two fronts has improved in recent years. For instance, Bujard et al.[23] have demonstrated that a resonance-based squid-like robot can enhance the swimming speed and efficiency to an extent that is comparable to that of an aquatic organism. Moreover, the robot should be able to steer itself and maneuver to access the required part of the asset. For instance, the dexterity of the manipulator arm of a turbine climbing robot is a key aspect. In case of a UAV, the beyond-visual-line-of-sight (BVLOS) system is a crucial determinant in enhancing its operational capability.

- *Sensing capabilities*: Another important requirement is the sensing capability of the robot. The sensors not only aid in navigation and control of the robot itself but also determine its operational capability in terms of conducting the remote or in-situ inspection of the asset, attaining feature-rich information, and performing non-destructive testing (NDT). Here, it is also important to assess the functionality of the sensors with respect to their operation in dynamic wind and wave conditions such as during foggy weather and in turbid sea water. Figure 5 illustrates the key sensors needed to control a typical robotic system and those needed to conduct an O&M task by gathering data from a FOWF asset.
- *Size and weight*: An important aspect of the offshore robots is their cumulative size and weight. The size of the robot should be large enough to accommodate the resident sensors and actuators/manipulators. Although keeping the robot small and light is desirable, it is also crucial to maximize the payload for various diagnostic instruments while maintaining ample power storage. This has ramifications in terms of power requirements and operational endurance of the mission. Hence, the cumulative weight of the robotic structure and its payload should be within the specified bounds where a trade-off has to be made between the operational requirements of the robot and weight bearing capacity of the entire system. Furthermore, there exist country-specific regulatory considerations for the particular sizes and weights of unmanned aerial systems.[24] In Figure 6, an illustration of the generic size and mass of different prototypes of climbing robots, UAVs, and ROVs is presented. While the actual values depend upon a variety of factors such as the operational requirements and the type of payload, the figure gives an indication about the relatively larger size of ROVs as compared to that of UAVs and climbing robots. This is partly due to the fact that ROVs have to navigate stronger currents and as such, require higher propulsive and power requirements, although the higher weight of ROVs becomes positively buoyant in the water.
- *Level of autonomy*: The level of autonomy of the robot describes the automation capability of the robot. For instance, Pilot Authorisation and Control of Tasks (PACT) framework distinguishes between the range of human support needed for various piloted systems.[26] Another framework is ALFUS,[27] shorthand for Autonomy Levels for Unmanned Systems, which is a generic framework and applicable to multiple unmanned system domains. The key components of this framework are the metrics along the three established axes or aspects. An illustration of these aspects for the UAV-based inspection of turbine blades is shown in Figure 7. This scenario represents a relatively high complexity of the operational environment, while the human independence and mission complexity aspects are in the middle. The aspects of mission complexity, environmental complexity, and human independence together characterize the autonomy of a specific robotic system. Different commercially available robotic systems can lie along the three axes, the autonomy profile of which can be assessed for a specific O&M activity. The objective for an autonomous operation is to achieve the missions as assigned by its human operator(s) through the designated human-robot interaction mechanism. While the state of the art includes remote operation of UAVs and tethered control of subsea robots under human supervision, the focus has increasing been moving towards highly autonomous robotic systems. These robots are capable to carry out asset inspection for extended duration of time and without active human intervention. Such systems need to acquire data, store it on their onboard computer, and send it to the onshore control system. Moreover, it is likely that the autonomy will be *tuned* for different scenarios. For example, transit out to the windfarm could be heavily automated but an inspection task may require more approval or input from a remote operator.

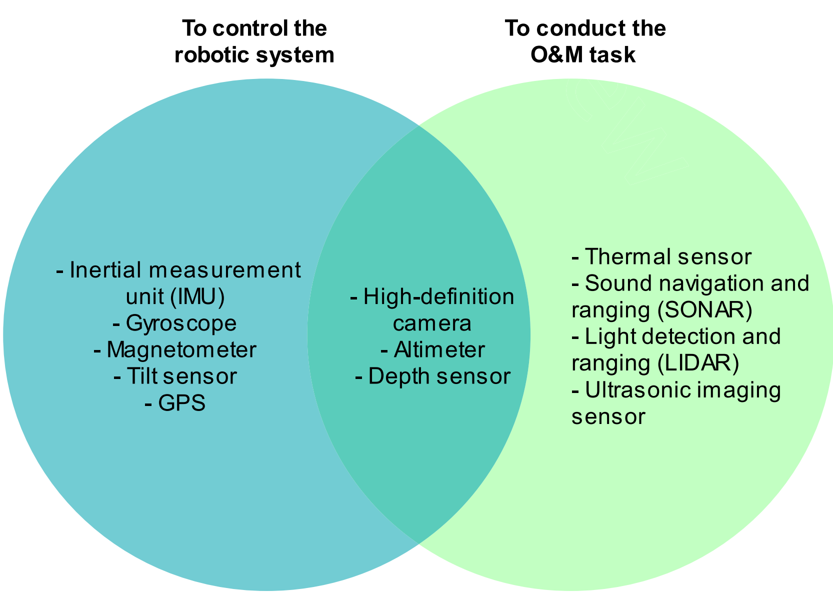

FIGURE 5 Sensors needed to control a typical robotic system and those needed to conduct the O&M task

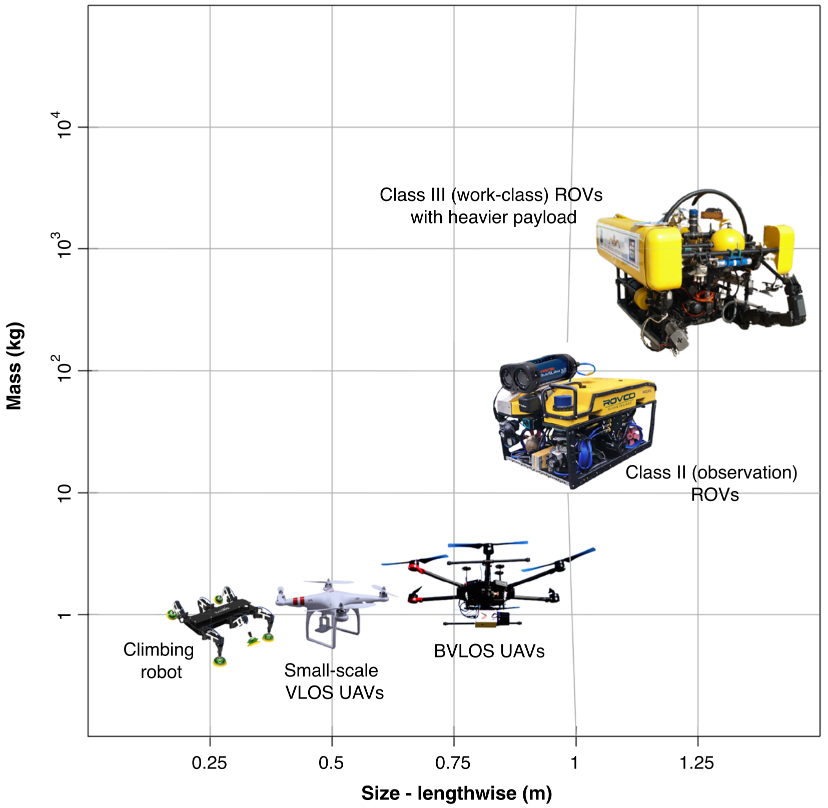

FIGURE 6 An illustration of the size and mass of the climbing robots, UAVs, and ROVs. All the values are indicative and serve only as a guide to scale different systems. Images courtesy: ROVCO[25] and Creative commons

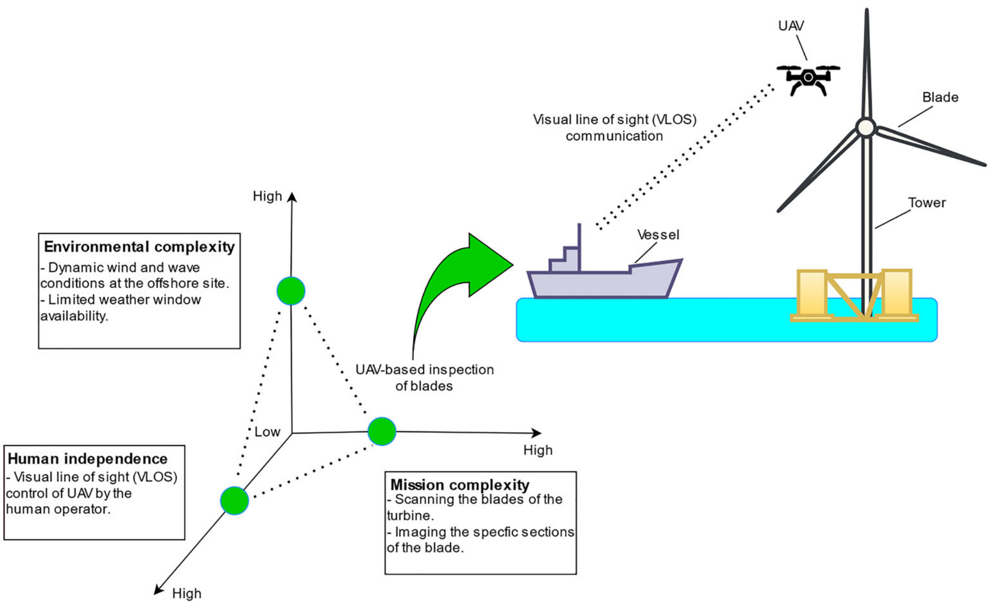

FIGURE 7 ALFUS framework[27] applied to the UAV-based inspection of turbine blades

3.1 | Climbing robots

In general, human operators with rope-access to the wind turbine conduct O&M tasks such as cleaning blades and inspecting structural defects in windy, high, and harsh environments. It is envisaged that a climbing robotic mechanism could replace some of these O&M tasks, improving efficiency in the process while also addressing the H&S aspects. In literature, different types of climbing robots are discussed based upon their design specification and functional requirements.[6,28] For this paper, the definition of climbing robots is restricted to be the machines that can move vertically or around the tower and blades of a wind turbine. The robot's access to the entire circumference of the tower and to the surface of the blade is imperative as it would determine the range of the O&M tasks that could be conducted. An example of such a climbing robot is shown in Figure 8. Based on their locomotion ability, climbing robots can be classified into the following two types:

- *Legged locomotion*: The key benefit of legged climbing robots is that they are highly adaptable to the surface structure, can clear obstacles and steps, and can transition from ground to wall with ease. In literature, various robots can be found with different number of legs and for different degrees of freedom. However, in terms of a smooth gait control, a large number of degrees of freedom contribute to a complicated mechanical structure and the associated control system. Consequently, the weight and torques are also increased. Hence, the robots with two[30] and four[31,32] legs are more common in literature.
- *Wheeled or chain-driven locomotion*: In case of a relatively smooth surface, climbing robots based on wheels and chains are used. The quick and continuous movement, as well as a simpler mechanical structure and control design, are significant advantages of wheeled or chain-driven robots. However, since these robots are unable to manage large steps or obstacles, they are less adaptable to varying surface characteristics and are limited to specific use-cases.

A comprehensive overview of climbing robots for inspection of vertical structures is presented by Schmidt et al.,[6] where a conclusion is drawn that although various prototypes exist for specific environments, very often the contradicting requirements of achieving a light-weight structure along with high maneuverability and dexterity capability, hinders their universal applicability. A maintenance robot for blade cleaning is presented by Jeon et al.,[33] where both motion of the mechanism of the robot and the cleanup mechanism based on water-jet can be controlled. A wire-tethered climbing robot is presented by Lee et al.,[34] where the applications of water-jet based cleaning and phased array ultrasonic testing (PAUT) are studied. The height and attitude control system are validated by conducting field experiments of the prototype. The results show that a robust control performance in terms of the motion of the robotic system is achieved. A modular robotic design is proposed in Sattar et al.,[35] where the robot is able to move vertically and rotate around the circumference of the tower. The robot scans the surface and conducts in situ X-ray tomography. This work was extended by Sahbel et al.,[36] where permanent magnets were used as an adhesion force for the robot. Experimental results show that the robot is able to adapt to the tapering diameter of the tower and the scanning arm was able to conduct NDT of the blade.

3.2 | Unmanned aerial vehicles

While relatively fewer studies have focused on climbing robots for O&M, aerial robots are gaining increased interest for conducting inspection and other remote sensing applications ranging from surveillance and infrastructure inspection to data acquisition, and aerial mapping.[21,37,38] The automated inspection of energy assets based on UAVs have gained significant attention in recent years. For instance, dust on solar panels in a large-scale solar farm can affect the power generation. In this case, UAVs can be utilized to monitor the condition of the solar panels.[39] Another use of UAVs in power systems that has been studied is automatic meter reading[40] along with the inspection of damage to the transmission lines.[41] In the case of FOWFs, a mature commercial offering is available where UAVs fitted with data acquisition technology are used to scan the surface of the turbine tower and blades. Advancements in UAV technology have led to increased automation of the task, reducing the onus on the pilot

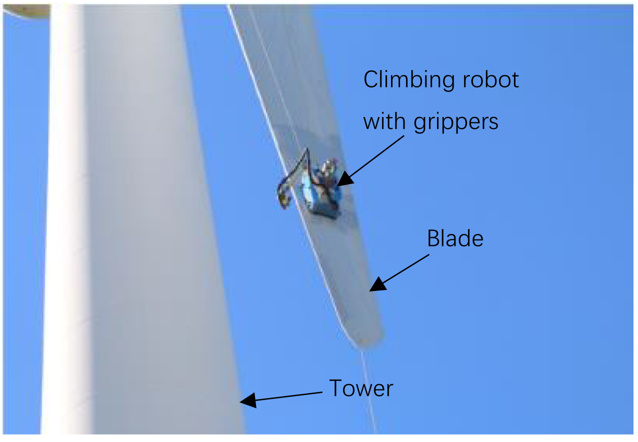

FIGURE 8 Climbing robot from rope robotics[29]

to manually maneuver the UAV. The data are then recorded and wirelessly transmitted back to the onshore control station. Post-processing is done to acquire imaging details, acoustic emissions, and the sensor measurements. Main benefits of using UAVs to inspect FOWF assets include (1) a more frequent and spatially larger access to the wind farm in a shorter interval of time, (2) the possibility to mount a variety of imaging and acoustic sensors onto the UAV for feature-rich data acquisition, and (3) the improvement in H&S aspects regarding manned access to the FOWFs. A few characteristics of UAVs in terms of remote inspection are as follows:

- *Specifics of motion*: UAVs are able to move in 3D space. The autopilot of UAVs is able to control the steady state flight along with the autonomous takeoff and landing of the UAV. Furthermore, vertical take-off and landing (VTOL) technology allows to control fixed-wing UAVs without the need for a runway. Nevertheless, certain aspects of the UAV motion need to be taken into account such as the range and endurance of the aircraft along with spatially covering the maximum area within a shorter interval of time. In case of a fixed-wing aircraft, the minimum turning radius restriction needs to be accounted for when considering flight paths with many curvatures. While most UAVs can adapt to variable weather environments, the offshore conditions such as strong winds need to be considered before the flight of the UAV.
- *Payload limitation*: The factors affecting a UAV's payload primarily include its design weight, onboard power storage unit, and the type of sensing equipment. The heavier the sensing equipment will be, the more thrust would be needed by the UAV, and hence, the power requirements would increase.
- *Specifics of communication*: UAVs have to maintain communication with the operators and in some cases, with the control station. A swarm of UAVs with BVLOS capability has the benefit in terms of an efficient control and larger swept area.[42] Furthermore, the acquired data need to be stored onboard and then transmitted to the control station. Here, sufficient data storage and transmission bandwidth need to be taken into account. Other connectivity challenges such as obstacle avoidance, GPS denial, and signal fading also need to be considered.

Recent research has benefitted from the advancements in machine learning algorithms for autonomous navigation and guidance of UAVs.[43,44] This is complemented by the use of imagery sensors such as LIDAR to acquire feature-rich data and send it to the onshore computers. Wang et al.[45] proposed the use of UAVs to detect the cracks on wind turbine blades based on image data acquisition. A typical control strategy entails directing the UAV such as a quadcopter to a position where it can concentrate on a reference object or feature using GPS signals.[46] After that, a high-definition or thermal camera is used to assess the target. It is pertinent to mention that the environmental conditions such as foggy and rainy weather can cause problems in the imaging, resulting in reduced usability and a limited detection of faults.

3.3 | Subsea robots

Recent advancements in subsea survey and inspection technology have allowed more detailed studies of the oceans and underwater structures.[47,48] Marine scientists and companies also have access to a wide range of underwater technologies, which are increasingly being used for a variety of purposes. However, owing to the increased offshore developments with varied scientific requirements, deep sea research remains expensive in terms of logistics and personnel requirements. Subsea technology is routinely used by the offshore oil and gas, and renewable energy industries for inspection, monitoring, and maintenance of assets in areas that are otherwise inaccessible to the marine personnel. In recent years, ROVs are increasingly being used at windfarms for conducting O&M activities along with de-risking offshore operations. The industry is developing new technologies for both underwater and topside applications in order to minimize the O&M costs and manpower requirements while also improving the safety and reliability aspects. For the case of a FOWF, two primary applications for ROVs pertaining to O&M are cited[49]: (1) export/array cable surveys and repairs and (2) scour and structural scans.

While the uptake of ROVs for inspection and monitoring has seen progress in recent times, significant challenges impede their full-scale exploitation in offshore sites. ROVs have very limited autonomy and must be tethered to the surface to receive power and be controlled from a technician. Higher operating costs for battery power and acquisition of trained technicians are stumbling blocks. On the other hand, autonomous underwater vehicles (AUVs), self-propelled underwater robotic systems powered and piloted by an on-board power source and computer, provide benefits in terms of higher mission capabilities, such as autonomous mapping and inspection of subsea structures. The drawbacks include limited operational range and increased on-board power requirements in case of longer duration missions. Both types of these subsea robots have attracted research and development efforts.[20] ROVs are classified into different types based upon their operational capabilities, as shown in Table 1. Classes I and II constitute observation vehicles with the ability to mount various sensors such as SONAR, high-definition camera, and lights. Class III is work-class vehicles with the ability to mount small manipulators in addition to more advanced sensors. Class IV vehicles are pulled through the water by a surface craft. These are heavier vehicles and are normally designed to carry out a specific underwater task such as burial of cables. Class V includes AUVs that are untethered, have higher autonomy and maneuverability, and can carry out mapping tasks for a longer duration of time.

An iterative design process of an inspection-class ROV prototype is presented by Capocci et al.,[50] where it is concluded that the final design of an ROV has to be based on the optimization of a series of trade-offs such as manufacturing cost, dry weight, power, and aerodynamic drag.

Sole emphasis on maximum thrust can lead to a corresponding increase in power requirements, tethering cross-section, and costs while also increasing the drag. Furthermore, aspects related to portability need to be taken into account as the deployment and recovery of sophisticated ROVs can be manually challenging and expensive. Cao et al.[51] have proposed the dynamic positioning of an ROV based on a nonlinear model predictive control. Results from hardware-in-the-loop simulation show that the controller is able to track the reference while rejecting external disturbances. Similar studies[52–54] show that the onset of advanced work-class ROVs coupled with robust control algorithms has resulted in their increased usage across different marine applications. The ROV prototypes Kaxan and PoseiBot are depicted in Figures 9 and 10, respectively. In terms of ROVs for FOWF, it is pertinent to mention that a vast majority of these systems would be deployed in shallow water along with experiencing rough wave and tidal conditions as opposed to deeper waters where the disturbances are minimal. Here, the highly dynamic and non-linear nature of the marine environment makes it critical that control aspects pertaining to disturbance rejection be considered. In this regard, typical approaches include disturbance estimation and rejection from in situ observations[56] or rejecting disturbances arising from steady or impulse perturbations rather than dynamic wave disturbances.[57] Walker et al.[58] presents experimental validation of the estimation of hydrodynamic forces acting on an ROV under regular and irregular waves of different significant wave heights.

TABLE 1 Classification of ROVs

Class	Description	O&M activity
I	Observation ROVs	Visual survey
II	Observation ROVs with payload option	Visual survey and light intervention
III	Work-class vehicles	Heavier payload with manipulators
IV	Towed and tracked vehicles	Cable burial, marine growth removal
V	AUVs	Autonomous inspection, spatial mapping

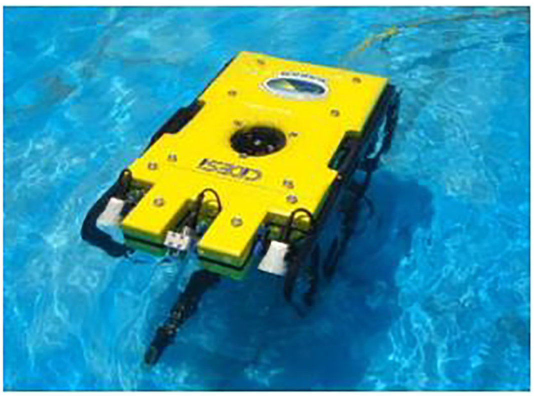

FIGURE 9 Class II ROV from Garcia-Valvodinos et al.[55]

FIGURE 10 Class I ROV from Molero et al.[53]

3.4 | Autonomous surface vessels

Autonomous surface vessels (ASVs), also known as unmanned surface vessels (USVs), have been the focus of significant research in recent years.[59,60] While the use of CTVs and SOVs bring flexibility in terms of payload and personnel capacity, their dependence on weather windows and higher leasing costs makes their use for longer duration of time less than optimal. Moreover, the typical cut-off point where CTVs can no longer be used and offshore accommodation is needed is 40 nautical miles (74 km) from the port.[61] With the anticipated construction of wind farms farther from the coast, a considerable reduction in O&M vessel costs could be possible by eliminating the need for large inspection vessels.[62] While the use of ASVs in defense and security domain has seen significant development,[63] their usage in offshore wind energy operations is still nascent. The use of ASVs has benefits in terms of conducting marine O&M for extended duration of time and without the need for enhanced crew deployment. ASVs typically utilize catamaran hulls for higher stability and have a modular design, whereby different types of payloads can be mounted based on the specific mission requirements. It is important to consider the varying degrees of autonomy for the ASVs and their effects on the O&M activities and task allocation. A classification of autonomy levels is provided by the Lloyd's Register where the tasks are divided into decision making, action taking and exceptions handling.[64] A more recent classification is presented by Schiaretti et al.[65] as shown in Table 2.

ASVs have demonstrated their ability to conduct mapping and obtain accurate models of the terrain above and below the sea level. This is done by combining laser scanning data with bathymetric data and then geo-referencing both data sets. In this way, a 3D model synchronized with temporal and spatial characteristics information is generated. Furthermore, ASVs have high maneuverability, can mount sensors of different types and weight, and have higher communication bandwidth which are pivotal in conducting large-scale bathymetry and surveying. Finally, removing the human operator from the offshore vessels allows to enhance human safety on the command-and-control operational framework in the offshore environment. ASVs also pose significant challenges in terms of their use in the wind industry owing to larger distances to the FOWFs and limited weather window availability. Of particular interest is the certification requirements for the use of ASVs in conjunction with manned vessels,[66] coordinated control of multiple ASVs, and devising command-and-control framework for ASVs to accomplish complex O&M tasks using real-time navigation and perception.

A categorization of robotics-based O&M for the turbine, BoP and logistics is shown in Table 3. The feasibility for a selection of O&M activities is highlighted in terms of *low*, *medium*, and *high*. *Low* feasibility refers to systems being in nascent stages of development, while the *medium* feasibility refers to systems that have been validated in scenarios representative of the actual FOWFs. *High* feasibility pertains to systems already in use with the future potential of upscaling the technology along with enhancing their usability in the FOWF domain. It is observed that the UAV- and ROV-based systems are more commercially developed and can conduct a range of tasks while the use of ASVs is relatively nascent and subject to extensive regulatory requirements.

4 | POTENTIAL AREAS OF RESEARCH

As the floating wind industry grows, there is a need to address research gaps pertaining to the incorporation of robotics and automation in this sector. In particular, the futuristic robotic systems capable of inspecting offshore assets under dynamic weather conditions along with conducting advanced sensing and actuation tasks need to be investigated. Furthermore, the associated design challenges and market adoption aspects need to be addressed. An illustration of this potential research outlook is shown in Figure 11, and the key identified areas are further discussed below.

TABLE 2 Autonomy level classification as presented by Schiaretti et al.[65]

Autonomy level	Description
0	Human is alone
1	Human is helped by systems
2	Human is helped by systems and agents
3	Autonomous path following vessel
4	Autonomous trajectory tracking vessel
5	Human in the loop
6	Human supervises the decisions making system
7	Human supervises the actions making system
8	Human supervises the exceptions handling system
9	Human supervises actions, decision, and exceptions
10	Fully autonomous

TABLE 3 Application of robotics for key FOWF-specific O&M activities

O&M activity	Robotic system	Typical payload	Feasibility	References
Turbine				
Blade inspection	UAVs	photogrammetry, video assessment and thermographic camera	High - UAVs widely used in industrial applications, high TRL	Pierce et al.,[67] Wang et al.,[45] Xu et al.[68]
	climbing robots	ultrasonic imaging, NDT	Low - mounting and control remains challenging, low TRL for wide-scale adoption	Sahbel et al.,[36] Sattar et al[35]
Tower inspection	climbing robots	photogrammetry, ultrasonic sensors	Medium - benefits in terms of fatigue testing, grout and structural health monitoring	Liu & Padrigalan, et al.[69]
	UAVs	visual and thermal imaging	Medium - 3D scanning of the tower cross-section	Schäfer et al[70]
Nacelle O&M	resident robots	grippers, visual imaging	Low - resident systems inside the nacelle can perform minor inspections Medium - UAVs can do external surveys, deploy small payload to assist personnel	Netland et al.[71]
Balance of plant				
Bathymetry mapping	ROV	SONAR	High - widely used in marine operations	Coggins et al.[72]
	ASV	SONAR, GPS/IMU for autonomous navigation	Low - challenging in terms of large-scale command and navigation of ASVs	Ferreira et al.,[63] Máthé et al,[43] Campos et al[73]
Inspection of array/ export cables	ROV, AUV	camera, grippers	High - increased usage of ROVs for fault detection and fatigue inspection in sub-components	Albiez et al. [74] Fahrni et al.[20]
Burial of export cables	ROV	camera, grippers	High - burial of cables is done using work-class ROVs, inspection of defects and fatigue in sub-components	Cho et al.[75]
Marine growth on subsea structures	ROV	SONAR, video assessment	High - widely used in marine operations	McLean et al.,[76] Restivo et al[77]
Metocean survey	ROV	camera, lights	Medium - widely used in marine operations, marine regulations need to be taken into account	Molero et al.,[53] García-Valdovinos et al[55]
Logistics				
Transport of components	ASV	data link, battery-powered	Low - deployment of higher autonomy level ASVs are subject to marine regulations and zone approvals, advanced navigation requirements for fleet control and coordination	Collins et al.[78]
Offshore operations center	ASV	data link, battery-powered	Low - autonomous mother vessels can deploy UAVs and ROVs, limited applications due to navigation and data communication requirements	Gray et al.,[79] Bernardini et al.[21]

4.1 | Future robotic systems

The development of advanced robotics for inspections is an ever-evolving process. Significant challenges remain in terms of autonomy, operational range, actuation, and capability of robots to perform the complicated O&M tasks under extreme marine conditions. To this end, many emerging robotic systems have been in development, leaning in on the advancement in industrial automation, control engineering, and artificial intelligence (AI). One such example is the use of soft robotics based on compliant and versatile materials. This results in an increased dexterity which aids in bio-inspired locomotion and navigation of the robot to access the otherwise unreachable and unknown subsea regions and structures.[80] An important aspect pertaining to soft and compliant materials is that they can protect the core electronic components and also mitigate the damage in case of collision with the asset. Although soft robots are cheaper to manufacture as compared to the traditional rigid structures, there exist challenges that hinder their large-scale adoption in the FOWF sector. These include navigating the rough waters, acquiring balance between the softness and load-bearing capacity of the robot, and the mounting of complex sensors and actuators for data acquisition and manipulation, respectively. Nevertheless, soft robotic systems provide promising potential for conducting O&M in the FOWF environment. Based on their functionality, these systems can generally be classified into two groups: (1) deterministic systems which achieve macroscale compliance through the force transition between truss-like structure[81,82] and (2) fluid-elastomer composites which are composed of soft materials to achieve mesoscale deformability in different loading directions.[81,83] Both systems could be utilized to conduct wind farm O&M especially the subsea components like mooring lines, array, and export cables. Another future trend is the deployment of resident subsea inspection platforms that are capable of conducting inspection for a longer duration of time, and without the active need of intervention. These platforms can be utilized for environmental surveillance and monitoring of the subsea infrastructure. For instance, Chellapurath et al.[84] have proposed a station keeping mechanism based on a legged robot which has shown to have higher station keeping efficiency (28%) than that of the commercial propeller based ROVs.

An emerging area of research is the development of hybrid systems where different types of robots are combined onto a single platform and work in unison to perform complicated tasks.[85] For instance, Conte et al.[86] have proposed a cooperative platform consisting of an ASV that can launch an ROV. Experimental results show that the ROV can autonomously navigate and track a target and send continuous video stream to the ASV. A similar system is shown in Figure 12. Another interesting example is the use of UAVs to carry and mount climbing robots on the turbine blade. While the UAVs can inspect the turbine from a distance, the mounted climbing robots can be more dexterous and achieve higher functionality in close proximity to the asset. CAROS (Climbing Aerial RObot System) is proposed by Myeong et al.,[88] which consists of a quadcopter equipped with four wheels. The quadcopter can adhere itself to a wall using aerodynamic adhesion force generated by the tilting of rotors. The control algorithm manages to regulate the orientation and landing speed of the quadcopter onto the wall. A similar system is proposed by Pope et al.[89] named as SCAMP (Stanford Climbing and Aerial Maneuvering Platform), which is a quadcopter capable to fly, perch, climb, and take-off again, as shown in Figure 13. It consists of carbon-fiber-based feet and tendons that control the gait of the platform as it climbs up a wall. Such robots can address the challenges associated with reaching different regions of the turbine tower and blades.[90] By mounting imaging sensors, the usability of these robots can be improved along with enhancing the scale of turbine inspections while removing the need for rope-access.

Recent advances in AI and machine learning have given benefits in terms of enhanced sensor functionalities and post-processing of the big data. In particular, the development of autonomous vehicles industry has resulted in LIDAR-based navigation sensors that have higher operational

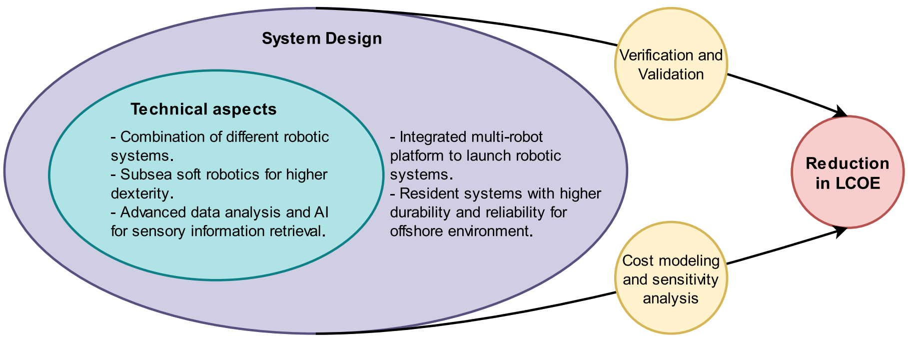

FIGURE 11 Research outlook for the adoption of robotics in O&M

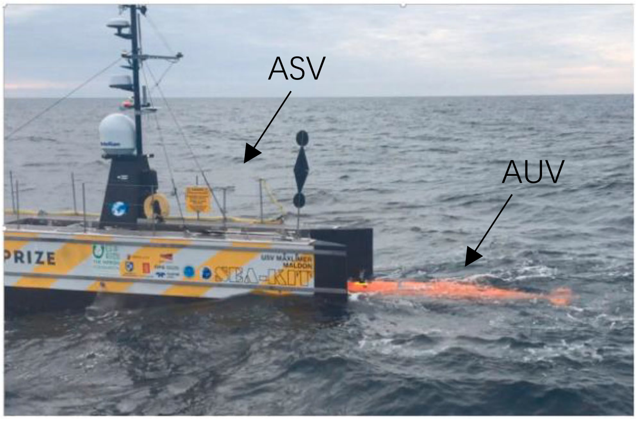

FIGURE 12 Sea-kit Maxlimer ASV recovering the HUGIN AUV. From Rumson[87]

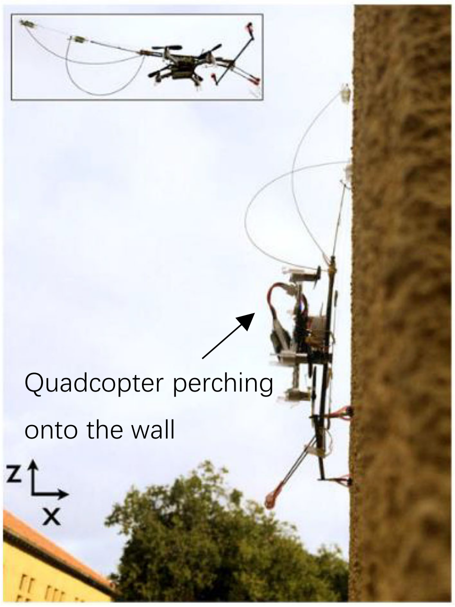

FIGURE 13 SCAMP as proposed by Pope et al.[89]

range and collision detection technology. This has also culminated in the use of LIDAR on UAVs for metocean mapping.[91] The availability of feature-rich data and higher processing power bodes well for the adoption of robotics-driven O&M. Furthermore, the modularization of design has resulted in low-cost robotic structures that can be retrofitted with the required sensors and actuators based on the mission-specific requirements. This results in cost reduction and greater operational flexibility of the robots. The acquisition of real-time sensor data is critical for the continuous monitoring of FOWF assets, which is then combined with the historical data to form a complete information flow. The high-speed processing and analysis of this data are becoming a key factor in planning and decision-making for O&M of FOWFs, along with the ability to deal with unforeseen situations and make efficient resource allocation.[92]

4.2 | Design challenges

4.2.1 | Integrated platform

One of the opportunities pertaining to wide-scale adoption of robotics in the FOWF sector is an integrated platform which can assist with the deployment of different robotic systems for O&M of assets. This integrated platform envisages both the design of a *mother* vessel that can launch *daughter* robots and a decision support framework for O&M task allocation and scheduling. Furthermore, the control and coordination of multi-agent systems such as a fleet of UAVs remain challenging in terms of meeting the standard marine regulations. In literature, there are recent examples of small platforms that have been devised to assess the costs and benefits associated with the usage of UAVs and ROVs. The conceptual design of a multi-robot platform named as Multi-platform Inspection, Maintenance, and Repair in extreme environments (MIMRee) is presented in Bernardini et al.[21] The platform includes an autonomous mothership, equipped with a fleet of drones and crawling robots that sails to the offshore assets and carry out inspection and repairing. More recently, the Atlantis[93] project aims to develop a pilot infrastructure in order to demonstrate key enabling technologies for the use of robotics in the offshore sector. This also includes developing a certification roadmap for the deployment of robotics and to measure the impact of it on the entire offshore wind life cycle.

4.2.2 | Verification and validation challenges

Compared with the onshore assets, remote and in-situ inspection of FOWFs is a long and potentially challenging undertaking. To this end, it is difficult to do extensive testing, verification, and validation of the O&M robotic systems. This is especially important for systems where robots have to work in unison with humans, and hence need to meet H&S and certification standards. In order to assess the operation of robotic systems for FOWFs, a number of verification and validation techniques[94] may be employed such as the following:

1. Extensive experimental and scaled testing of the robotic systems on representative FOWF platforms.
2. Iterative validation including developing and improving system design based upon the continuous feedback from industrial end-users.
3. Simulation-based testing and training of the robotic systems and their operators, respectively.
4. Formal verification methods to ascertain the logistics and temporal functionalities of the robotic systems and their limitations.

Along with specifying the hardware and software performance, formal verification also includes aspects related to the explainability of AI-based systems. Remote operation of robots in marine environment poses several complex challenges. The lack of access to the local system, in case of a centralized control system, leaves the human operator reliant on sensory information and feedback to navigate. This can hamper the operator's situational awareness. On the other hand, in case of automation complacency, the operator can become too reliant on the robotic system that can lead to reduced perception of threats. The precision required to remotely operate a robot and if done for longer duration of time could lead to an increase in stress responses, which, if not mitigated, could lead to accidents. Moreover, insufficient training and a lack of transparency in system design could result in confidence and trust issues between the human operator and the robot, especially in the case of unforeseen and critical situations.

4.3 | Market challenges

4.3.1 | O&M cost modeling

In order to assess the O&M costs associated with the robotic systems and to identify the key cost drivers, it is imperative to forecast the OPEX for O&M activities. Variable O&M costs constitute the majority of the wind farm's OPEX as opposed to the fixed costs, which pertains to factors such as human resources, insurance, and leasing costs. In literature, various O&M cost models have been presented and their benefits assessed, although most of these models are developed in-house and their detailed description remains confidential. Typically, the models accept inputs in terms of the turbine and BoP specifications, failure rates, weather conditions, weather window availability, and the O&M strategy. The outputs are given in terms of the OPEX costs, with some indications on the vessels and personnel required, energy production, capacity factor, and time- and energy-based availability. The overall objective is to improve performance metrics such as a reduction in asset downtime and the LCOE. An overview of the existing cost models prior to 2011 is presented in Hofmann et al.[12] with more recent reviews presented by Welte et al.[95] and Judge et al.[96] A cost–benefit assessment of remote inspection of nacelle is presented by Netland et al.,[71] where NOWIcob tool is used to simulate the O&M costs. It is demonstrated that for an offshore wind farm, a remote inspection system combined with condition monitoring improves availability and reduces the LCOE, as compared to the condition monitoring alone.

4.3.2 | Valuation methodology

Robotic systems with low-to-medium technology readiness levels (TRLs) are characterized by the uncertainty of projected costs (e.g., capital and operational expenditure) and benefits (e.g., return on investment, reduction in LCOE). This is because investors often forego capital intensive investments into robotics and automation systems that could bring benefits in the long term. To this end, investors need a comprehensive product valuation to aid in the decision making. An important aspect in OPEX forecasting is the valuation methodology used. In general, net present value and discounted cash flow analysis is used to determine the price required for an investment to breakeven. While this is a widely used methodology, there are other aspects pertaining to future investments in innovative systems that need to be accounted for.[97] A valuation methodology based on options theory is presented in Ho et al.,[98] where the mathematical framework for single-stage and multi-stage investments is developed. Real options analysis is the methodology used to capture the inherent complexity and uncertainty in innovation-driven investments.[99] Real options allow to model different scenarios such as the timeframe of making investments and the resultant effect on long-term value creation. The refinement of the valuation methodology aids in incorporating the policy making vector in the early-stage design process, whereby investors can forecast the value of their investments before the final investment decision can be granted.

5 | CONCLUSION

The FOWF industry is destined to grow in the future, and as such, the demand for efficient O&M practices with lower expenditures is expected to be more pronounced. Restricted weather windows, long-distance logistics, and the need to ably maneuver, gather high quality data, and conduct O&M of FOWF assets are challenging tasks for which the traditional methods are not sustainable. In this paper, a range of robotic systems and their applications for the FOWF-specific O&M are presented. While the adoption of robots in industrial sector has seen significant traction in recent years, various challenges remain for their wide-scale incorporation into the FOWF domain. Hereby, a non-exhaustive list of discussion points include the following:

1. In terms of autonomous offshore logistics, the advancement in battery technology augurs well for the use of battery powered ROVs which will allow tether-free access along with increasing the endurance of UAVs.
2. The usage of ROVs for burial and inspection of underwater cables have seen considerable progress. The challenge remains in terms of increasing the TRL of existing systems, and enhancing the operational range of ROVs, which can eliminate the need for divers and expensive tether management system.
3. While the use of ASVs is still in nascent stage, benefits in terms of improved safety and higher efficiency can be reaped by their usage in longer-duration missions and especially under harsh weather conditions.
4. The development of autonomous industrial robots has culminated in the availability of advanced yet low-cost sensors for data acquisition. For instance, thermographic cameras and ultrasonic sensors can greatly aid in gathering feature-rich data from the FOWF assets in comparison to traditional manned methods of visual inspection.
5. The automated gathering and retrieval of data are ushering in the usage of AI and data-driven approaches for continuous maintenance and inspection. This could aid in better management of available resources and increased availability of the FOWF assets.
6. The modular design and low-cost versions of climbing robots and UAVs aid in their applicability for various O&M tasks. Sensors and payload of different characteristics can be mounted as per the specific mission requirements.

For the FOWF industry, the benefits of enhancing O&M through robotic systems range from efficiency in terms of cost and resource management to enhanced and accurate data gathering. Furthermore, the long-term impacts of FOWF infrastructure in oceans can be assessed and understood. With this knowledge comes improved decision-making for conducting continuous O&M at FOWFs deeper into the sea. The robotic system providers need to be cognizant of the emerging trends in O&M while also taking into account the regulatory and certification barriers. This can improve the TRLs of the robots and provide a viable commercial roadmap along with enhancing the value-chain in the robotics-based O&M sector.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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