Impact of robotics on the operation and maintenance of offshore wind turbines

A review

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Abstract

This article analyses the impact of robotics on the operation and maintenance (O&M) of offshore wind turbines (OWTs), with a particular emphasis on the challenges and benefits. As the world's reliance on renewable energy, particularly offshore wind, increases to reduce climate change, the growing number of OWTs requires effective O&M. Challenges consist of logistics, accessibility and high costs. The paper presents the application of climbing robots, unmanned aerial vehicles and underwater robots to overcome these challenges.

The combination of multiple robotic platforms, such as autonomous surface vehicles and autonomous underwater vehicles, represents a collaborative approach to O&M. Obstacles include the need for accurate navigation, building trust between humans and robots, and research into artificial intelligence.

In conclusion, the integration of robotics in O&M presents considerable advantages, increasing efficiency, safety and cost-effectiveness. Further progress and research into artificial intelligence are crucial in achieving complete automation, which will transform the O&M of OWTs.

Keywords: offshore wind turbine, operation and maintenance, robotics, climbing robots, underwater robots, unmanned aerial vehicles, multi-robot platform, LCOE

1 Introduction

Renewable energies are being expanded worldwide to reduce CO_2 emissions and to counteract climate change. Offshore wind in particular has a significant impact on meeting these targets. One reason for this is that, in addition to the limited area available for the development of wind energy on land [1], a comparable system at sea requires less area [2]. Furthermore, installation sites located further from the coast offer an opportunity to harness stronger winds, allowing for higher and more consistent energy production. This also helps to mitigate conflicts of interest, such as social acceptance [3]. Meanwhile, the increasing number of turbines is having an unavoidable impact on the O&M of offshore wind parks. As a result, there has been an increase in the use of robots in the O&M of OWTs. The incorporation of robots presents both challenges and opportunities.

This article evaluates the effects of robotics on the O&M of OWTs. It focuses on the challenges and benefits of using robotic systems for the maintenance of OWTs. The paper also highlights the emerging trends in this field and presents practical application examples.

2 Methods

This chapter offers an overview of the methodology implemented in the creation of this review article. The objective is to present readers with a clear understanding of the methodological approach and to guarantee the transparency and reproducibility of the analyses performed.

Initially, the systematic literature search was carried out through the *Google Scholar* search engine, employing a range of keywords, including those listed previously. Next, a literature map was developed with assistance from the AI tool *Research Rabbit*. The method enabled a re-evaluation of sources and facilitated the discovery of new, pertinent literature. In addition, the writing assistant *Deepl Write* was used to improve text quality during writing.

The application of literature research and evaluation in conjunction with AI tools enabled a comprehensive approach to creating this review article. The use of supporting tools ensured the quality of sources and the development of a well-founded overview of the research field.

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3 Operation & Maintenance of offshore wind turbine

3.1 Current state

The O&M of OWTs is more and more dependent on logistics and transport due to the increasing distance from the mainland. Crew transfer vessels (B), as shown in figure 2, are the current means of transport. For maintenance work further offshore, service operation vessels are used as floating hubs. They provide accommodation for offshore technicians and store spare parts for OWTs. A service operation vessel can accommodate up to 88 technicians at sea for 4 weeks. Helicopters (D) can be used to supplement ships. They reduce transit time and improve access, but come at a higher cost [3, 4].

All vehicles carry divers (C) and rope-access technicians, who typically carry out inspection and repair work on the OWT. The technicians face difficult environmental conditions that may compromise safety. Furthermore, adverse weather conditions that hinder accessing the OWT elevate their downtime. This, together with logistics and transportation costs, is a significant contributor to O&M costs [5].

3.2 Importance of effective Operation & Maintenance

Early detection or prediction of damage is essential to reduce costs. This can prevent further damage that would necessitate replacement of system components. Failure to identify faults in a timely manner can result in extensive maintenance work and consequently increase the downtime of the OWT. This leads to a decrease in electricity generation and consequently an increase in the levelized cost of electricity (LCOE) (refer to figures 4 and 5 in [6]). In particular, due to the increasing output of recently installed turbines.

Therefore, the primary objective for every wind farm operator is to minimize their maintenance expenses while maximizing operational hours [7]. With an average annual failure rate of 8.3 per OWT and a growing number of turbines, these developments highlight the difficulties associated with the O&M of OWTs [1, 8].

3.3 Current Challenges

As previously stated, OWTs have an advantage over onshore turbines in terms of available area. However, onshore turbines have a decisive advantage in terms of LCOE, as shown in figure 1. These costs depend on several factors, such as the environmental conditions at sea, accessibility and O&M costs.

To meet these challenges, it is necessary to develop efficient and cost-effective O&M strategies, as described by Ren et al. [9] to ensure continuous operation of the OWT. This requires balancing factors such as capacity, timing, route planning or risk, among others, to ultimately achieve the maximum component life, maximum wind turbine operating hours, minimum repair and maintenance costs for the operator, and minimum downtime. Weather and environmental conditions due to wind and sea also influence this planning [9]. In the following chapters, the challenges of the O&M of OWTs are discussed and implemented in more detail.

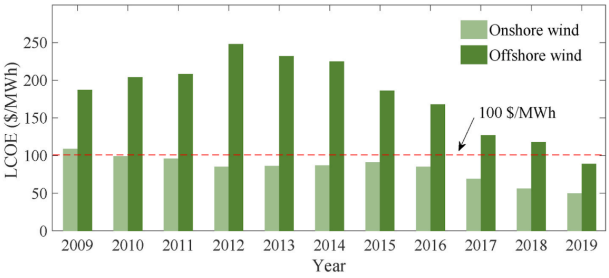

Fig. 1: Comparison of LCOE for onshore and OWTs between 2009 and 2019 [9]

3.3.1 Environmental conditions & Accessibility

One of the biggest challenges in operating and maintaining OWTs is the harsh environment at sea. This places a constant strain on the equipment, transport vehicles and technicians. For example, wave action and salt water affect the corrosion of the turbines. In addition, the high wind speeds are beneficial for higher power generation, but they also put continuous stress on the rotor blades. Both result in shorter lifetimes and an increasing number of inspections of turbine components and infrastructure. Carroll et al. [8] show that there is a strong correlation between increasing wind speed and increasing failure rate (see figure 10 in [8]). This alone leads to a 33% higher failure rate due to wind speed compared to onshore wind turbines.

Due to the prevailing environmental conditions, OWTs face a number of challenges. The high wind speeds and wave movement hinder the accessibility of these turbines by helicopters or transport vessels, necessitating the use of more expensive ships equipped with motion-compensating gangways. Furthermore, the transportation of equipment, components, and personnel has become increasingly challenging. When technicians are sent from shore to perform maintenance, the increasing distance of installed OWTs from shore results in longer repair times and smaller weather windows available for maintenance. Consequently, work must be rescheduled, thus increasing downtime and subsequently the LCOE [1, 9].

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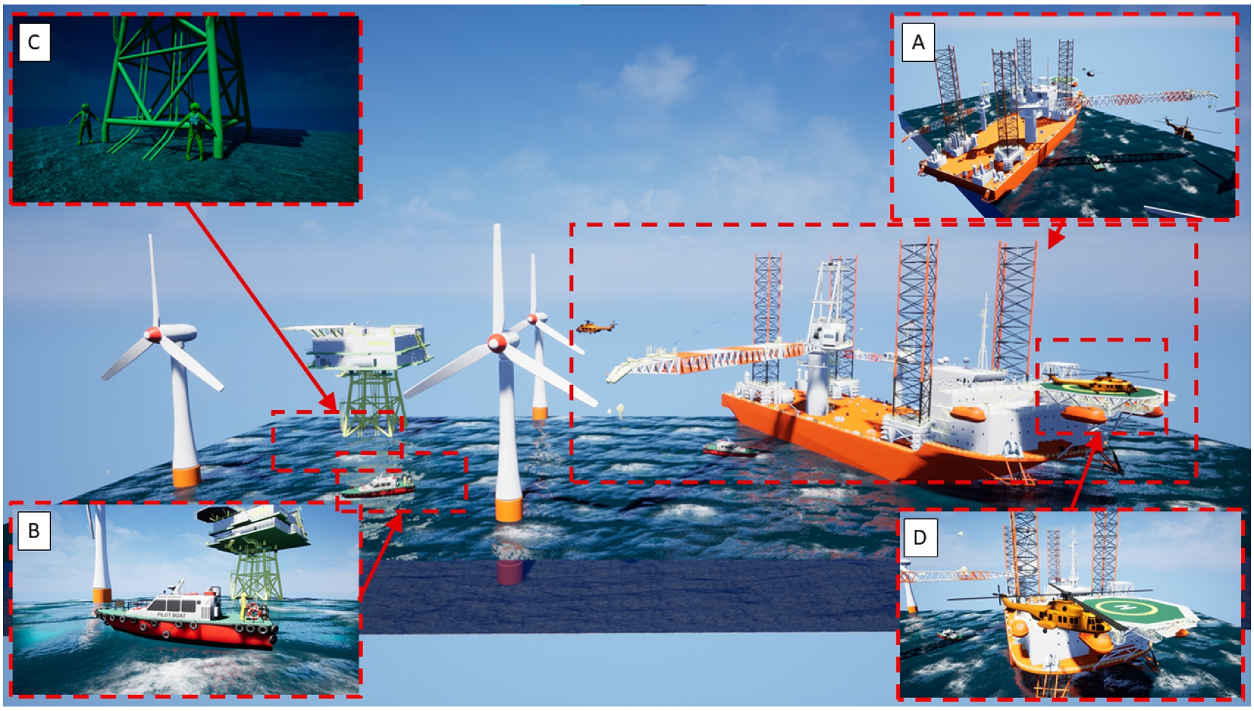

Fig. 2: Current assets and the supporting infrastructure within the lifecycle of an OWF array [4]

3.3.2 Operation & Maintenance costs

OWTs exhibit a higher failure rate under high wind speeds. This results in increased repair and maintenance costs. Although wind farm operators strive to mitigate this issue by selecting turbines with low failure rates and minimal maintenance needs [8], the expenses involved in the O&M of an OWT account for 30 to 35% of the total life cycle costs. For onshore wind turbines, these costs are lower, ranging from 25 to 30% of the life cycle costs [3]. In terms of total investment costs, the difference is considerably greater with OWTs accounting for 23% of the investment cost, compared to 5% for onshore turbines.

The offshore sector incurs average maintenance costs that are two to three times higher than those on the mainland. Mitchell et al. [4] argue that this is mainly due to shipping and logistics, which account for 60% of operating costs. They also note that accessibility, and therefore the transport of technicians to OWTs, accounts for 80% of O&M costs. As OWT installations increase, repair and maintenance work expands, and more transport and personnel capacity is required further driving up these costs [9].

As a result, OWTs have a noteworthy drawback in terms of O&M costs as compared to onshore turbines. This highlights the importance of implementing effective strategies. As a solution, robots can be employed to overcome this challenge, rather than relying on maritime technicians.

4 Robotics

Current trends in the industry indicate the continued development of new robotic technologies for OWT maintenance. This trend is underlined by the findings of Mitchell et al. [4], which show a sharp increase in the number of patents. The various technological and robotic advancements consequently offer differing advantages.

For structures above water, this work focuses on the two technologies, unmanned aerial vehicles (UAVs) and climbing robots, using the example of rotor blades. This is due to their high failure rates in OWT, as previously mentioned. Figure 3 in [8] illustrates that the failure rate of OWT blades per component ranks fifth. In terms of system component failures, the rotor blades rank second and third in average repair time and material costs respectively, at approximately 290 hours and 90,000€ (see Figures 13 and 14 in [8]). Regarding the average number of technicians required to repair a component, rotor blades top the list with over 20 technicians (see Figure 15 in [8]).

The failure of the blades is caused by the environmental conditions and forces. The rotor sheets are exposed to large loads due to strong winds, rain, snow, and ice, which in turn affects the aerodynamics [2]. In addition, the blades are mainly made of fibre-reinforced composite materials, which are relatively new materials for use in such environments. Although composite materials display no external damage when subjected to forces, they can still be damaged internally. These damages can lead to greater consequential damage over time. Regular checks are therefore essential [10].

4.1 Climbing robots

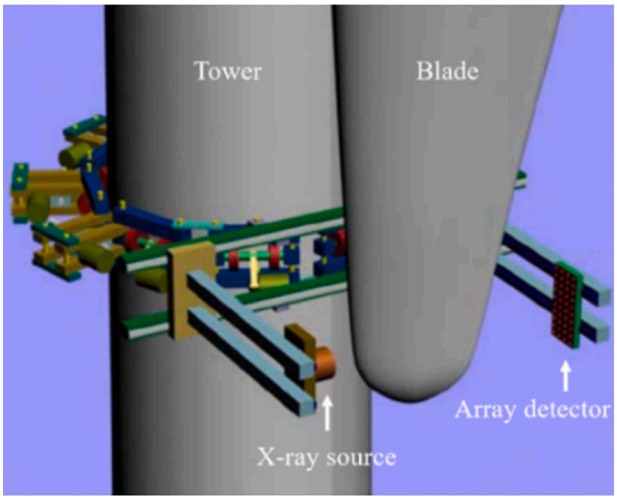

Fig. 3: Schematic illustration of a climbing robot for inspection of a OWT blade [2]

Nevertheless, carrying out the inspections poses a significant risk to the cable access technicians and is prohibited at wind speeds of 20m/s and above [9]. To overcome this, climbing robots can be used to inspect the rotor blades, allowing inspections to be carried out in harsh conditions. A modular climbing robot capable of spanning the entire tower is shown in figure 3. By doing so, a better distribution of forces and a higher payload can be achieved. Furthermore, the ring's diameter can be adapted to the tower using feathers while climbing. For rotor scanning, an arm equipped with measuring instruments can be installed on one side of the robot. Using two motors mounted on the modules, Sattar et al. [10] built a prototype that allows the robot to move horizontally, vertically and spirally on the tower of the OWT.

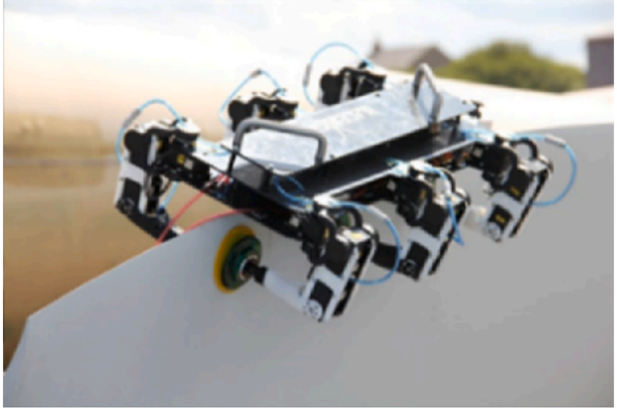

Fig. 4: friction-based climbing robot [2]

In addition to the increase in safety, the use of climbing robots makes it possible to work directly on the blade. Unlike UAVs, which need to keep a safe distance from OWTs, robots provide a more stable scanning platform, leading to more accurate data and precise results in identifying damages. In relation to O&M costs, a climbing robot, as shown in figure 4, has the potential to lower them by approximately 30% [2].

4.2 Unmanned aerial vehicles

UAVs can inspect various components of the OWTs with greater efficiency. Thus, the disadvantage of UAVs having to maintain a safe distance from OWTs is offset by their flexibility as an advantage. However, adverse weather conditions like wind or rain may pose operational challenges. In addition, lower payloads and inefficient flight times are caused by limited battery capacity. In summary, while UAVs have a lower payload and need to maintain a safety distance, they offer greater efficiency and flexibility [2].

Table 1 indicates that the inspection costs can be reduced by approximately 90% when an inspection with drones is compared to an inspection by technicians at the same OWT. This is due to the considerably reduced inspection time. An OWT inspection takes a technician 7 hours, but a UAV within the visual line of sight (VLOS) can reduce this time to 15-30 minutes. With full automation and no human intervention, the UAV can complete the inspection in just over 6 minutes. To do this, path points are created around an OWT, as shown in Figure 7 in [6] or Figure 3 in [2]. These are then flown off from the UAV. As noted by Poleo et al. [6], there is currently no definitive information or study on the lifetime of these systems in offshore operating conditions. It is believed that drones have a lifetime of 4,000 flight hours.

Overall, the faster inspection time can lead to significant cost reduction while enhancing safety by eliminating the need for height work [6]. If the UAV is not operational, another one can maintain the system by overlapping usage areas [4].

4.3 Underwater robots

For structures below the water surface, underwater robots are presented in this section. Their applications include the creation of 3D models and the performance of inspections and maintenance for foundations or mooring systems. The robots are able to hold their position in water currents of up to 1.5m/s or follow road points like UAVs [2].

Mooring lines for connecting the floating foundations of OWT to the seabed require regular maintenance. However, a detailed inspection of the mooring lines only takes place every five years on the surface [3]. If any damage to an mooring line is detected, and a replacement is required, the costs can vary from £0.6 million to £1.2 million [4]. As the number of turbines connected by multiple mooring lines continues to increase, maintenance demands will also rise

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Tab. 1: Comparison of Directly incurred (DI) cost of inspecting 139 individual wind turbines once a year: OPEX and revenue lost for technicians and UAVs based VLOS case according to Poleo et al. [6]

Item	Technicians		UAVs	
	DI Cost per time unit	Time-units required	DI Cost per time unit	Time-units required
Workforce (Technicians)	£18/h	139*3*7 [a]	£18/h	18*2*7 [f]
Workforce (boat)	£18/h	139*7 [b]	£18/h	18*7 [g]
Transport (boat)	£600/day	139 [c]	£600/day	18
Consumables	£1500/year	4 [d]	£5.35/h	18*7 [g]
Onshore Admin	£20/day	139 [c]	-	-
Revenue lost (worst case)	£237/h	139*7 [e]	£237/h	139*0.5 [h]
Training	-	-	£1500/year	1
Insurance	-	-	£1500/year	1
Civil Aviation Regulation Fees	-	-	£750/year	1
Total	Up to £392 k per year		Up to £39 k per year	

On 8th December 2023, the exchange rate between the British pound and the Euro was 1£ = 1.17€.

[a] Based on 3 technicians, inspecting 139 turbines and assuming each turbine takes 7 h to inspect.

[b] Based on utilising 7 h a day for 139 days.

[c] 1 day per turbine.

[d] 1 per person involved (3 wind turbine technicians and 1 boat operator).

[e] Based on shutting down the turbine.

[f] Based on 2 UAV operators being able to survey a 139 turbine farm in 18 days (8 turbines per day).

[g] 18 days for 7 h each.

[h] Assumes turbine needs to be shut down for 30 min for inspection.

correspondingly. Hence, there is a necessity for autonomous systems in this field of maintenance that can conduct maintenance activities more safely, deeper, less expensively and more efficiently than divers.

An example of an underwater robot that can perform underwater inspections, maintenance and repairs is the *Eelume*, shown in figure 5. Its flexible body is equipped with batteries, lights, sonar, cameras, sensors and positioning systems, and it can remain underwater permanently either autonomously or under the control of an operator [1]. Integration into the wind farm can be achieved by using underwater garages, which function as both storage and charging points for the robots. Maintaining the robots presents a challenge due to the environmental conditions. Moreover, these conditions might affect the photos or videos captured by the robots [2].

Fig. 5: The Eelume underwater robot was developed by NTNU and Equinor [1]

4.4 Multi-robot platform

An important emphasis in the integration of robots is the development of collaborative robots that form a complete system and can autonomously perform inspection, maintenance and repair tasks on OWTs. Research conducted by Khalid et al. [3] describes how an autonomous surface vehicles (ASVs) is capable of transporting and launching an autonomous underwater vehicle (AUV) as a part of an extensive system. During the inspection, the AUV can stream the recorded video to the ASV. The two devices can also communicate with each other via data exchange, thereby enabling recovery. A comparable system is shown in figure 6.

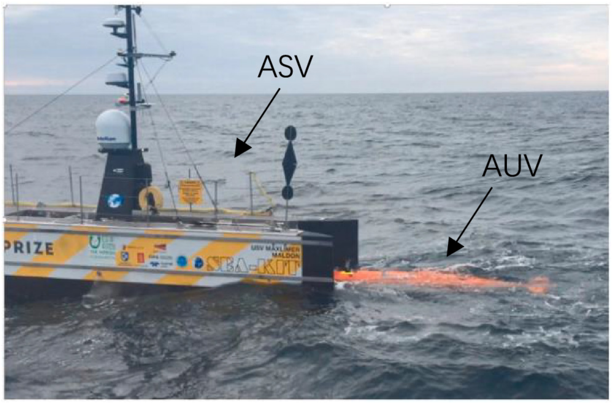

Fig. 6: Sea-kit Maxlimer ASVs recovering the HUGIN AUV [3]

Bernardini et al. [5] describe a similar system in which the ASVs brings a unit of UAVs and climbing robots, as shown in figure 4, to the OWTs. Both robot types then inspect the turbines, where the UAVs can be used as both inspection and transport units for the climbing robots, see figure 3 in [5]. To do so, the challenge is to land safely on the rotor blade without causing damage, and to recover the climbing robot safely.

5 Future challenges in the implementation of robotics

Besides the challenges in the interaction of multiple robots, trust between human and machine is probably the biggest challenge. When autonomous robots operate in the sea and act beyond the VLOS, there can be problems with the understandability of the robot's behaviour. This problem may be exacerbated by further or full automation of OWT O&M, as human operators increasingly rely on robotic data for decision making [5].

Another challenge, for example, is the introduction of more precise navigation systems that will enable UAVs to get closer to OWTs and thus carry out more accurate and safer inspections. Additionally, there is an effort ongoing to optimise the payload and battery capacity of UAVs to extend their operational time beyond the current 30-minute limit [2].

6 Conclusion

The development and implementation of robots to assist in the O&M of OWTs is increasing. This is due to the ability to enhance efficiency, productivity and safety when compared to the current maintenance process. The comparison of technicians and UAVs has indicated that the costs of inspection alone can be reduced by up to 90%. Since O&M costs account for approximately one-third of the total life-cycle costs of an OWT, significant savings can be achieved.

Furthermore, the significant reduction in inspection time per turbine from 7 hours to up to 6 minutes means that the number of inspections can be increased. Moreover, the robots have been designed with enhanced weather resistance, which can help to minimise turbine downtime and ultimately lower the LCOE. Overall, it is becoming apparent that the incorporation of robots in the O&M of OWT offers numerous benefits.

7 Outlook

However, much further development and practical effort is needed to fully automate O&M. It is worth exploring the potential application of artificial intelligence, which was not analyzed in this article. The increasing number of OWTs also requires more robots, which collect a large amount of data. The analysis of these data could be more accurate and faster with the use of artificial intelligence.

All of the factors described above will lead to robots and artificial intelligence replacing the current workforce. One possible initial step is the remote control of robots by human operators within the VLOS. Subsequently, remote control can be extended beyond the VLOS. Both steps build trust in the technology. This shift in workplace dynamics has the potential to significantly restructure roles and responsibilities, necessitating that employees acquire additional skills for efficient collaboration with the robots. Consequently, the ways in which OWTs are managed will change significantly in the future.

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