Performance of Unmanned Vehicles for Offshore Wind Turbines

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Operations and maintenance of Offshore Wind Turbines (OWTs) are challenging, with manual operators constantly exposed to hazardous environments. Due to the high task complexity associated with the OWT, the transition to unmanned solutions remains stagnant. Efforts toward unmanned operations have been observed using Unmanned Aerial Vehicles (UAVs) and Unmanned Underwater Vehicles (UUVs) but are limited mostly to visual inspections only. Collaboration strategies between unmanned vehicles have introduced several opportunities that would enable unmanned operations for the OWT maintenance and repair activities.

UVs offshore wind turbine unmanned operations

1. Introduction

The Operation and Maintenance (O&M) of a Wind Turbine (WT) are very important. Within the O&M activities, the maintenance part plays a crucial role to ensure the longevity of a WT as well as to lower the cost of its daily operation. Proper maintenance activities such as regular inspections and repairs will reduce WT downtime, thus reducing losses in energy output [1]. However, maintaining a WT requires extra effort due to the complexity of tasks performed at a high-rise tower and the hazardous environments it is operating in. These levels of complexity increase tenfold concerning the Offshore Wind Turbine (OWT) due to its location. O&M of an OWT is more challenging than the normal WT due to the sea waves' action and high wind which could damage the OWT structure [2]. Even more, human operators are also exposed to more hazardous environments at sea during the transit and accessing times of the asset and during the Inspection, Maintenance, and Repair (IMR) operations. Due to the increase in Health and Safety (H&S) issues for human operators as well as to minimize the cost associated with IMR activities, unmanned operations are viewed as promising solutions which also lead towards the net zero strategy to reduce significant carbon footprint by 2050 [3].

Although Unmanned Aerial Vehicles (UAVs), Unmanned Underwater Vehicles (UUVs), and Unmanned Surface Vehicles (USVs) have already been deployed for unmanned operations of the OWT [4][5], they are mostly used for visual inspection operations such as for Wind Turbine Blade (WTB) and subsea surveys. Most major industries have begun to deploy unmanned techniques in their IMR activities; however, this is not the case for the OWT industries, probably due to the major challenges they face, such as being located far from land, within the treacherous sea environments, as well as having limited capabilities in current unmanned technologies. Unmanned systems can be classified into fully autonomous, semi-autonomous, teleoperation, and remote control [6]. The commonly used mode for current unmanned operations at the OWT is remote control, where a UAV is used for visual WTB inspection and Remotely Operated Vehicles (ROV) for underwater surveys. However, full autonomy for inspections using UAVs and UUVs is rapidly being deployed today. Nonetheless, the deployment of these autonomous vehicles also faces greater challenges and issues, under Beyond Visual Line of Sight (BVLOS), especially with energy and communication issues [7]. Hence, these limitations further hinder the potential for conducting unmanned IMR for OWT.

Several efforts have been initiated to advance the potential of implementing unmanned IMR for OWT. Among the solutions are to install a localized power charging station near the OWT farms using fixed stations [8][9][10] or using a docking vessel either crewed [11] or uncrewed [12][13]. The latter solution is seen as moving forward due to many benefits it brings, including reducing carbon footprint, increasing operator safety by remaining onshore, and increasing efficiency with continuous operations [14]. Furthermore, the use of uncrewed vessels also functions as a communication hub that connects the UAVs or UUVs to the onshore Ground Control Station (GCS) [15]. A recent technological breakthrough in terms of real-time communication has shown a positive trend in deploying uncrewed vessels for offshore energy activities. The presence of an uncrewed vessel or a USV near an OWT farm has enabled a new kind of unmanned network that has the potential to be utilized in a collaborative manner. With sound collaboration strategies between multiple UVs, it has the potential to solve many issues surrounding the IMR operations of the OWT.

2. The State-of-the-Art of Unmanned Vehicles Performing in Offshore Wind Turbines Inspection, Maintenance, and Repair Operations

The types of UV currently available for unmanned OWT inspection are either remotely piloted [16][17] or autonomous [18] and can either be a UAV [19], USV [13], or UUV [20]. Unmanned inspections carried out by UAVs are mostly performed using visual-based approaches [17][18][19][21]. However, UAVs which can perform close-contact Non-Destructive Testing (NDT) inspections are also available [22], although they are very limited. While the UAVs perform inspections for OWT structures above sea level, the UUVs on the other hand are currently being used to perform unmanned inspections for underwater OWT structures [23][24][25]. Meanwhile, unmanned inspections using USVs are also being carried out for the purpose of surveying underwater seabed for OWT farms [13], as well as monitoring the scouring of pile foundations [5]. However, these multiple types of UVs are currently known to operate independently, hence limiting the potential or capability to perform unmanned OWT maintenance or repair works.

Although it is easier for a UV to perform a visual inspection of an OWT, the lack of extra hands or tools, as compared with manual operation by human operators, means that it proves to be a very difficult task for a single UV to perform maintenance or repair work. For example, a UAV with limited capability to carry heavy equipment or to carry a set of different tools will not be able to perform maintenance or repair work. A USV on the other hand, would not be able to reach a very high-rise OWT tower to repair the blades, or reach an undersea OWT structure or undersea cables. Meanwhile, a UUV might be able to perform maintenance and repair works on subsea cables or OWT undersea structures but would still require a nearby vessel or station to charge its batteries, for tethering purposes or to relay inspection and maintenance data.

To enable extra capabilities to perform maintenance and repair, a UAV built with dual 5-axis robotic arms has been developed [26]. This platform has the capability of carrying up to 10 kg of payloads, thus enabling the ability to carry and to manipulate tools for IMR purposes. This UAV can also be capable of changing tools during flight. However, the maximum flight time is only 30 min, which might be sufficient for most maintenance tasks but is insufficient for OWT deployment. The remotely operated UAV will also have to depend on a nearby supporting vessel, as the flight time might be insufficient for offshore operations. Moreover, a human operator is needed onboard the vessel to charge the batteries.

Alternatively, drone swarms for OWT operations are currently being designed and developed [27][28]. However, the solutions remain off-limit for maintenance and repair purposes as these drones are only capable of performing visual inspections, though at a faster rate or at a wider scale. Moreover, a swarm system needs a very complex algorithm to perform maintenance or repair in a collaborative manner. Nevertheless, several efforts utilizing multiple drones in other fields have been observed, with the potential to be implemented for WT maintenance and repairs such as for carrying heavy payloads [29][30][31] or assembling structures [32].

Moving forward, significant efforts which are highly viewed as the most viable solution are currently being developed, which relate to the integration of multiple types of UVs that can be implemented to collaboratively perform unmanned OWT IMR (e.g., UAV and USV [33][34][35][36][37][38][39][40][41][42], USV and UUV [43][44][45][46], UAV and UUV [47][48], or a combination of all UVs [49][50][51][52]). In addition, the use of crawler robots has also been proposed in this collaborative system to increase the capability and flexibility of WT maintenance and repairs [53].

Table 1 briefly summarizes the works that have been put forth related to collaborative unmanned vehicles. Basically, it highlights the relevant contributions for each work which have the close potential to be implemented within the OWT IMR operations.

Table 1. Summary of UVs collaboration types, purposes, and methods

Types	Ref.	Purposes	Methods	Application
UAV-USV	[33]	Recovery	- Using a fiducial marker located on a USV for accurate UAV landing.	General
	[34]	Recovery	- Using a three-stage fiducial marker on a USV to improve landing stage detection by UAVs.	General

Types	Ref.	Purposes	Methods	Application
	[35]	Communication platform	- Using a distributed dynamic network topology for fulfilling effective communication for establishing required formation between UAVs and USVs based on an ad hoc network.	General
	[36]	Path planning, navigation, communication platform	- Using aerial mapping and real-time aerial visual assistance provided by UAV for USV path planning and safe cruising. - Using datalink telemetry as a communication relay when a USV is in a GNSS-denied area.	Monitoring of rivers and dams
	[37]	Recovery, transportation	- Using adjustable buoys and a unique carrier deck for safe landing and transporting of a UAV on a USV. - Using 3D path planning by generating a sequence of guide points for a UAV towards the USV deck. - Using integrated ultrasonic sensors on a USV to ensure UAV landing positioning accuracy.	General
	[38]	Recovery	- Using an infrared receiver on a UAV to detect infrared beacons on a USV. - Using a two-phase UAV precise landing method to land on a USV. - Using USV control and path-following algorithms to guide UAV.	General
	[39]	Launch and recovery	- Using a robotic recovery system for a water-landing UAV onto a USV.	General

Types	Ref.	Purposes	Methods	Application
			- Using a solar-powered automated USV platform.	
	[40]	Communication platform	- Using location-based beam steering algorithm to establish high-speed communication links between a GCS, a USV, and a UAV.	General
	[41]	Power supply	- Using a wireless charging pad on a USV platform to charge UAV's batteries.	Monitoring of water pollution
	[42]	Power supply	- Using power umbilical tethers from a USV to supply power which results in longer UAV flight time.	General
USV-UUV	[43]	Localization	- Using an Extended Kalman Filter (EKF) augmented by ultra-short baseline (USBL) range and visual-data-based localization from a USV to enhance UUV localization.	General
	[44]	Launch and recovery	- Using a stern platform to recover a UUV onto a USV. - Using a sonde transmitter for communication from a USV to a UUV Central Unit. - Using optical communication from a UUV to the USV to send back sonar data and underwater positions.	Surveying of ports and critical infrastructure
	[45]	Recovery	- Using visual lighting and acoustic guidance strategies for the Docking and Line Capture Line Recovery (LCLR) system to recover a UUV onto a USV.	General

Types	Ref.	Purposes	Methods	Application
	[46]	Localization, power supply, communication hub	- Using a waypoint tracking algorithm on a USV to provide relative heading and coordination to UUV. - Using an underwater cable to supply power from a USV to a UUV and to transfer a large amount of data from a UUV to a USV.	Underwater survey
UAV-UUV	[47]	Navigation	- Using the position on the aerial view acquired from a UAV to manually guide a UUV towards a target.	Survey and waste management
	[48]	Communication platform	- Using an acoustic device attached to a UAV, data can be transferred from a UUV directly to a floating UAV.	Underwater survey
UAV-USV-UUV	[49]	Mission planning, path planning, localization, navigation	- Using visual imagery from a UAV and a UUV, a USV acts as data and an intelligent hub to autonomously plan and distribute survey missions. - Using a USV GNSS positioning system to guide the UUV through underwater communication. - Using underwater visuals to guide USV from colliding with underwater obstacles.	Surveying of floating targets
	[50]	Path planning	- Using a cooperative search algorithm based on random simulation experiments and asynchronous planning strategies, an underwater target can be detected by a UAV, USV, or UUV. -	Underwater, search-and-track mission

Types	Ref.	Purposes	Methods	Application
			Using the information of the detected target position, a UUV will track the underwater target.	
	[51]	Communication platform	- Using an underwater acoustic channel characterization to enable effective communication between UAV, USV, and UUV.	General
	[52]	Power supply, communication platform	- Using tethered connections from a USV to UAVs and UUVs to prolong operation time. - Using Wi-Fi and UHF antennas on a USV, data from UAV and USV can be communicated to the onshore ground control station.	Inspection and survey missions on offshore infrastructures
USV-UAV-CR	[53]	Transportation, power supply	- Using a USV with battery charging capability to transport UAVs and CRs to an offshore wind farm. - Using a UAV or UAVs to carry CRs to an inspection site.	IMR for offshore wind farms.

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