DOE

MARKET RESEARCH STUDY

DRONE & ROBOTIC INSPECTION OF WIND TURBINES

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1.0 Introduction

This report explores the role that drones and robotics increasingly play with wind turbine operations and maintenance. A modern land-based wind turbine will last 20 years on average depending on environmental factors such as wind speeds and turbulence intensity. For offshore wind additional factors come into play such as cyclic loading of foundations.[1, 2] The lifespan of both land-based and offshore wind turbines can be extended by monitoring performance and implementing the correct maintenance procedures for that tower in that location. This practice is referred to as lifetime extension and has historically been conducted by wind technicians who repel by rope along the length of turbine blades while examining the structure for defects and damages.

The average wind turbine contains over 8,000 components, however, the most important include the **rotor blades, blade pitch control system, yaw system, nacelle, gearbox, and generator**.[3,4] Components such as wind turbine blades are more prone to damage and are often replaced during the life of the turbine. A 2022 article on the root causes of mechanisms of failure in wind turbine blades cited that "With an estimated 700,000 blades in operation globally, there are, on average, 3800 incidents of blade failure each year."[5] Performance challenges are exacerbated by offshore operating conditions and include corrosion and biofouling in addition to the more common materials fatigue challenges which all turbines experience. Turbine inspection and maintenance adjusted for the environmental conditions and the wind turbine structure are vital for lifetime extension.

2.0 Turbine Inspection and Maintenance

Wind turbine maintenance involves processes such as routine inspections, cleaning, lubrication, and repairs to keep the turbines running smoothly. If wind turbines are not inspected and maintained on a regular basis, they can break down and cause serious property damage and injury.[6] Regular maintenance on wind turbines includes checking the blades for cracks and damage from exposure to environmental conditions, inspection of the gearbox for wear and tear, generator inspection, checking bearings for signs of damage, regular cleaning of the nacelle which collects dust and debris, keeping the rotor free of debris, and checking the wiring and oil regularly.[7] The global wind turbine maintenance market is projected to be worth $27 billion by 2025, and growing as a CAGR of 8%.[8] In comparison, the global drone wind turbine blade inspection market size was worth $319.27 million in 2022 and expected to grow to $601.47 million by 2030.[9]

> The longevity of a wind turbine is mainly dependent on the quality of its components and regular maintenance. The main wind turbine component that wears out over time is the blades. The blades are made of composite materials subject to fatigue and can eventually crack. The leading edge of the blades is also subject to erosion from wind and rain. Another factor that can damage wind turbine blades is lightning. Lightning can cause a blade to break or catch fire. In addition to the blades, a wind turbine's gears, bearings, and other mechanical components can also wear out over time. Proper maintenance can extend the lifespan of these components.
>
> One way to damage a wind turbine is to overload it with too much wind. It can happen when a turbine is poorly designed or when the winds are stronger than expected. Overloading can cause the blades to break and damage other turbine parts. Another way to damage a wind turbine is to operate it in a too harsh environment. It can include operating in a desert environment where there is a lot of sand and dust in the air. The sand and dust can wear down the components of the turbine and eventually cause it to fail. Turbines in hurricane-prone areas will not last as long as those in more stable locations. To avoid damaging a wind turbine, following the manufacturer's recommendations for operating and maintaining the turbine is essential. It is also vital to inspect the turbine regularly and replace any worn parts.[10]

2.1. Types of Inspections

Wind Turbines are typically inspected two to three times a year. However, with the use of drones and other autonomous tools, there is the potential for more frequent inspections. The main goal of inspection and maintenance is to decrease the levelized cost of energy. The following wind turbine lifecycle stages require inspection and monitoring services to ensure quality and performance:

- During and post-manufacturing
- Transporting the components to the work site
- Building the turbines on site
- Inspections for warranty claims
- Tracking construction progress

- Operational performance of the turbines
- Preventative maintenance and damage assessment[11]

2.1.1 Blade Inspections

Blades are exposed to operational wear and weather and environmental conditions which can lead to damage. Turbine blades are increasing in size, adding more stress for the components. Surface inspection of the blade involves using cameras, drones, or humans to identify issues such as surface cracks, leading-edge erosion, lightning or bird strikes, delamination, or leading or trailing edge splits. If defects are caught early, they can be repaired before major damage is done and prolong the life of the components. Sub-surface inspection involves the internal structure of the blades using thermal imaging, shearography, ultrasound, electromagnetic, radiography, and visual inspection. Physical inspection of the blades involves technicians climbing and visually inspecting the blades, although they don't have the capacity to search the whole internal structure. For offshore wind turbines, internal corrosion from the salty air is a potential problem.[12]

2.2. Common Wind Turbine Failures

Some of the common issues that lead to the need for turbine maintenance include gearbox failure, blade failure, and generator failure. The gearbox accounts for about 13% of the overall cost of the turbine. Most often gearbox failure is caused by contaminated lubrication, improper bearing lubrication, uneven load distribution, low service factors, and extreme wind levels. Blade failure is the most common reason for maintenance and the production of larger blades leads to more opportunities for failures, with an estimated 3,800 blade failures each year, out of the 700,000 blades in operation globally. The causes of blade failure include joint failure, erosion, cracks in the blade, and split fibers. Generator failure is caused by contaminated lubrication, extreme temperatures, excessive vibration load, and irregular voltage management.[13]

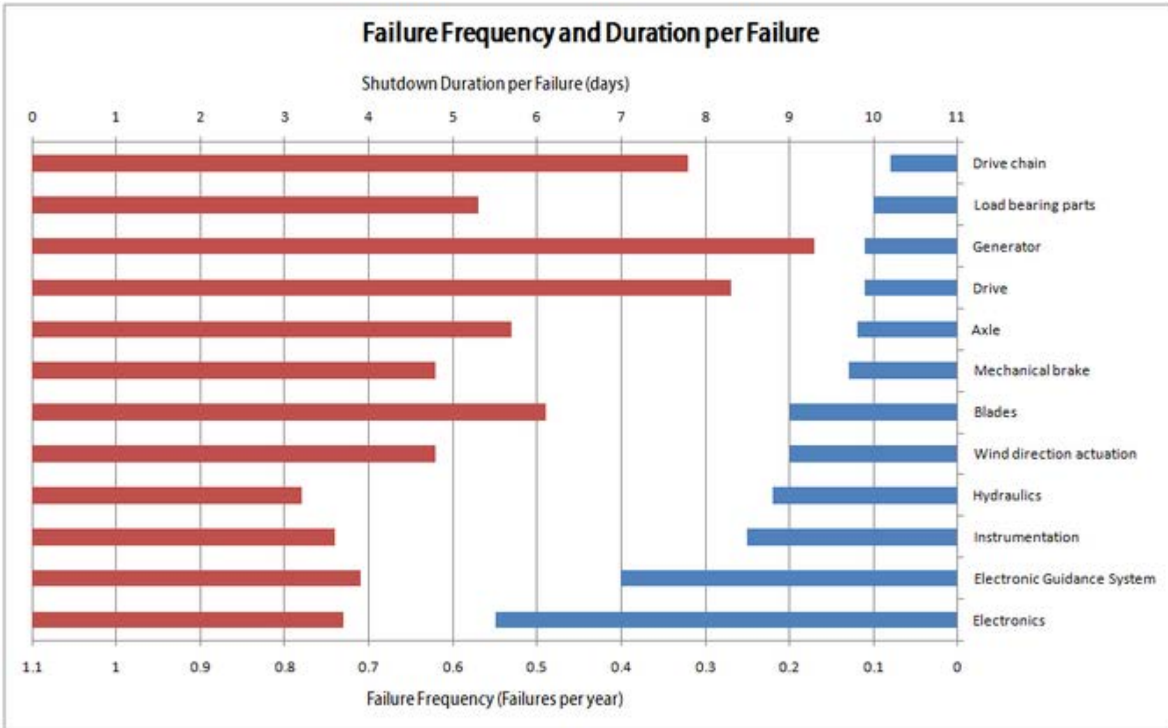

Figure 1: Failure Frequency and Duration Per Failure
Source: Enerpac, 2021[14]

2.3. Turbine Inspection Processes

There are two main ways to manually inspect a turbine; rope access operation and ground-based monitoring. Both inspection routes are explored in more detail in this section as well as the alternatives provided by drones and robots. Additional steps are needed to transfer technicians and equipment to offshore wind turbines.

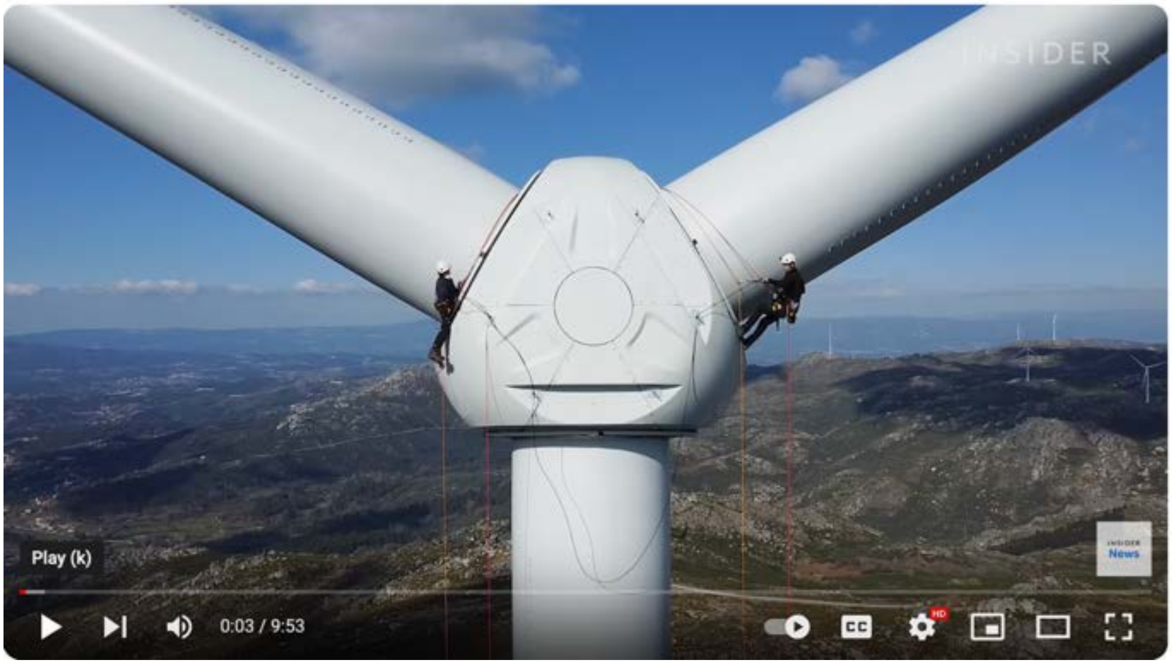

Figure 2: Wind Turbine Technicians and Inspection
Source: (Click here to see video)

2.3.1 Rope Access Operation

In order for a rope access operation inspection to occur, the rotors must come to a standstill with the lowermost blade pointing down at the six o'clock position while a group of three or more technicians ladder up the tower and then, while tethered to a rope, the inspectors make their way down the nose cone looking for any damages. The biggest challenge of this operation is the obvious risk to the technicians.[15] For offshore inspections, the process is similar with technicians climbing to the top of the turbine and abseiling down each blade using ropes to identify defects or damages. This inspection process depends on good weather conditions and calm waters.[16]

Abseiling or repelling is the controlled descent down a steep slope.

2.3.2 Ground-Based Monitoring

Ground-based monitoring involves using high-resolution cameras from the ground to monitor the turbines. However, the challenge with this method is that even the best cameras would not be able to provide a full picture of the condition of the turbines.[17] For offshore wind turbine inspections, a camera is situated in a boat about 70-80 m away from the turbine to take pictures of the components. The pictures are put together to create one large image of the turbine that technicians can inspect for defects. This visual inspection process does not have a consistent quality and can miss defects. Recently, nondestructive testing (NDT) techniques are being used to provide detailed information such as location and size of the defects. The most popular methods currently used are ultrasonic testing, acoustic emission, fiber optics, thermographic testing, and radiographic testing.[18]

2.3.3 Offshore-Specific Turbine Inspection

Offshore wind farms require more maintenance and operation costs because of their remote location and exposure to harsh environmental conditions. The current practice for maintenance requires vessels to transport technicians and equipment to the turbines to conduct close inspection and maintenance. Following visual inspection, technicians use rope access to carry out any required maintenance. The cost of maintenance is about 25% of the wind turbine installation cost over 25 years of service. The cost is attributed to the downtime required during the inspection and the daily use of the crew transfer vessels to and from the wind farms. Safety of the technicians is another concern of the current processes.[19] Drone-based inspection for offshore wind involves two technicians, one to control the drone and one to control the boat. The drones can capture high-quality images from different aerial views and then these images can be processed and analyzed for defects. Drones can detect damage such as fatigue cracks, surface corrosion, galvanic corrosion, pitting, stress corrosion cracking, and erosion.[20]

Table 1: Damage Mechanisms of Offshore Wind Turbine Detected by Drones

Damage Mechanism	Causes
Fatigue cracking	Cyclic loading
Corrosion (uniform, localized, etc.)	Exposure to corrosive materials such as mineral or carbonic acids or aqueous environments, seawater and humid or condensing environments
Pitting corrosion	A form of extremely localized corrosion that leads to the creation of small holes in the metal. The driving power for pitting corrosion is the depassivation of a small area, which becomes anodic while an unknown but potentially vast area becomes cathodic
Corrosion fatigue	Corrosion fatigue is caused by crack development under the simultaneous action of corrosion and cyclic stress
Erosion	It occurs due to the effect of weather conditions such as rain and hail
Mechanical damage	Extreme wind/wave loadings

Source: Robotics, 2021[21]

2.4. Drone Inspections

Another method of turbine inspections that could address the challenges of the previous two methods is drone-based inspections. Drones can be used to inspect the whole turbine from the blades, towers, and nacelles. Inspection techniques include visual, thermographic, acoustic, Lidar, and internal blade inspection.[22] Both autonomous and controlled drones can be used for wind turbine inspection. Using autonomous drones can lead to a 70 to 90 percent drop in inspection and downtime costs. Hours of downtime from lack of regular maintenance or ineffectual inspections can rack up a large financial toll. UAV inspection can shorten the time of inspection to 15 minutes versus an all-day event for the rope access method.

Additional inspection equipment includes wheeled crawlers and fiberscopes, although both are bound by spatial limitations. Drones can be used for internal inspections with their infrared cameras and ultrasonic payloads that can detect irregularities below the surface.[23]

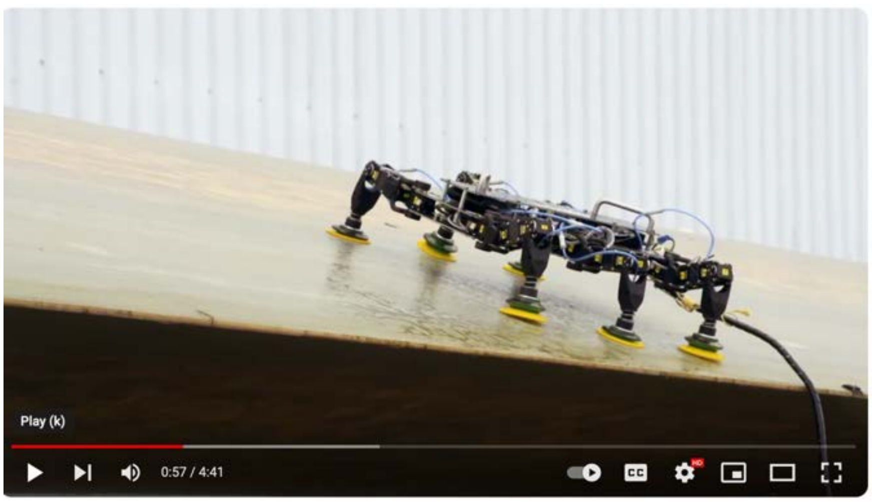

Figure 3: BladeBUG: The Game Changer Series

Source: Click here to see video

Drone inspections provide new opportunities for the automation of operation and maintenance of offshore wind farms as well. Using autonomous tools can greatly reduce the cost and remove the health and safety risks to the technicians that would normally use rope access to physically inspect the turbines. **Blade inspection, maintenance, and repair (IMR)** robots such as the one provided by BladeBug, can provide remotely operated and controlled inspection and repair of turbine blades. However, the need for manual deployment and retrieval of the robots to the turbine blades makes the rope access technique still necessary. Research is being conducted on using a multirobot system to automate the process of deployment and retrieval of the IMR robot for offshore inspections.[24]

2.4.1 Autonomous Drone Navigation

For autonomous tools to be successful inspecting wind turbines, they need to be programmed to navigate around and through them as well as deal with challenging weather. Different solutions include algorithms for landing pad detection and control for navigation, an onboard vision-based positioning system relative to a target, a LiDAR-based local navigator for a ground vehicle for obstacle avoidance, and LiDAR sensor for creating a 3D map of wind turbines and fusing LiDAR data with GPS. Different algorithms for control and navigation are required for different turbines as their designs may differ and the meteorological conditions create challenges as well. A UAV using a global navigation satellite system (GNSS) is susceptible to measurement errors and loss of signals. Solutions to this problem include visual localization and navigation and the use of ultra-wide band technology and anchor points.[25]

Figure 4: Vaisala-NREL Discusses the Value of Lidar

Source: Click here to see video

The steps to detecting failures using UAVs are to capture images, preprocess the images, turbine tower detection and recognition, turbine blade detection and recognition, and turbine hub detection and recognition.[26]

2.4.2 Coordination Among Autonomous Robots

The use of a multirobot system for turbine inspections requires good coordination and high-level cooperation to work autonomously. Because of the challenges of operating autonomous systems in remote environments, a semiautonomous platform is often preferred with an operator controlling the drone/robot. Currently research is being conducted on how to integrate cooperation and coordination into the systems for extreme environments. Each of the different robots have different roles and these roles need to be coordinated across the system. An example of multiple coordinated roles is seen in the retrieval of an IMR robot which requires the robot controller to perform actions such as preparing its attaching features, orientating the robot in the necessary direction, and performing an embrace position for the retrieval while the UAV flies toward the IMR robot and prepares the attaching module.[27]

Figure 5: The MIMRee Project
Source: Click here to see video

2.4.3 Mechatronic Systems for Deployment and Retrieval

Mechatronic systems that are used for the deployment and retrieval of robots to wind turbine blades include the robot deployment interface (RDI), the link-hook module (LHM), and the on-loading attaching module (OLAM). These have been used with the BladeBug MK II IMR robot, which is a hexapod wind turbine blade IMR platform. Along with the IMR robot, the platform includes a retrieval UAV system and the deployment UAS. The global mission planner (GMP) collects the feedback from the robots and broadcasts instructions for a coordinated operation.[28] An image of the robot/UAV/UAS is included in the following figures.[29]

The deployment procedures assume the system is prepared onshore with the IMR robot manually coupled with the UAS and locked in the undercarriage. When the UAV arrives at the turbine blade, it scans for a safe location for deployment. After the UAS lands securely and deploys the IMR robot, the UAS returns to a designated area on the Autonomous Surface Vessel (ASV).[30] The picture included below illustrates the deployment scenario.

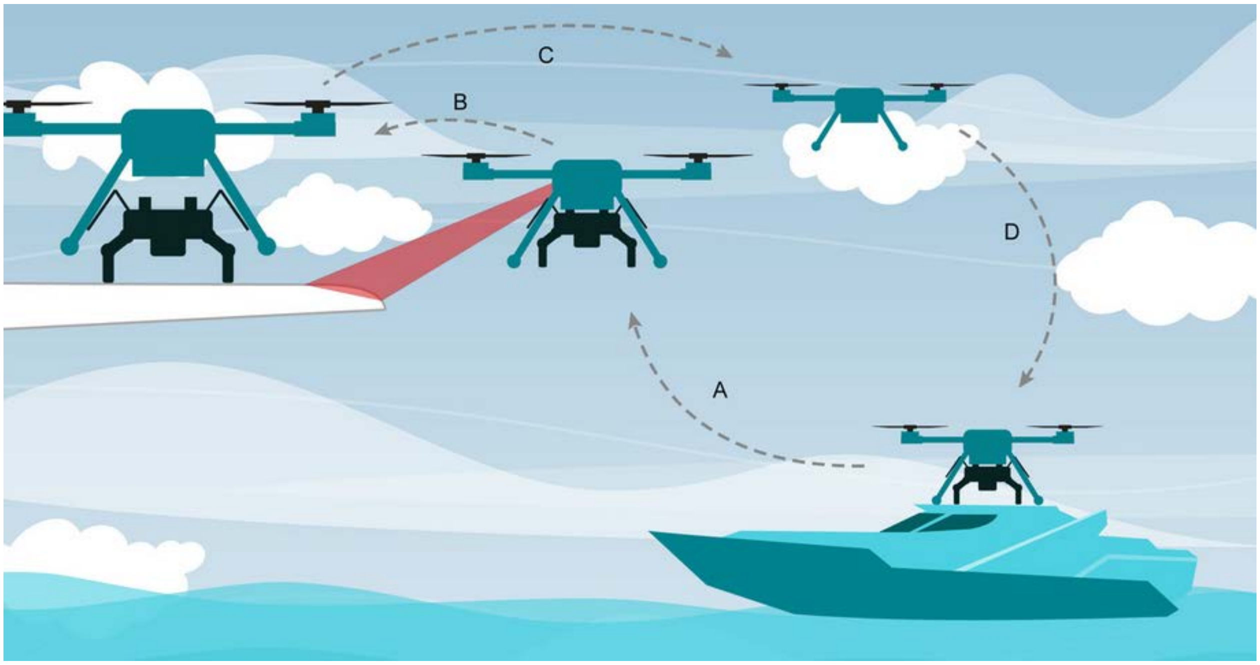

Figure 6: BladeBug deployment procedures: (A) the deployment UAS launches from the ASV carrying BladeBug, and scans the blade surface to locate a safe landing spot; (B) the UAS navigates to the landing spot, slowly descends to land and deploys the payload; (C) the UAS carefully takes off from the turbine blade, and; (D) returns to the ASV.

Source: Journal of Field Robotics, 2023[31]

The retrieval process involves the UAS navigating to the wind turbine blade based on GPS coordinates. The OLAM unfolds and prepares for engagement. The UAS aligns with the OLAM, couple between the two systems is achieved by engaging the locking and hook mechanism. After the LHM detects successful engagement, the UAS returns to the ASV to release the robot.[32]

2.5. Maintenance Process

Wind farm maintenance could use any the processes to keep wind turbines in working order. During this process maintenance workers conduct activities such as lubricating moving parts (gearboxes and bearings), checking connections within the system, and resolving major issues. The wind turbine operators use both preventative and predictive maintenance processes. Sensors are located in the turbine that send various types of data back to the wind farm's maintenance team. Information on lubrication levels, vibration, temperatures, and foundation displacement are collected by the sensors and help to plant maintenance activities. There is also regularly scheduled lubrication and maintenance checks (every six months).[33] Some of the steps of wind turbine maintenance are listed out below.

- Pre-inspection checks – ensuring all parts of the turbine are in working order,
- Cleaning wind turbine components – making sure the parts of the turbine are clear of dust and debris,
- Oil changes – wind turbine oil needs to be changed for operational efficiency,
- Replacing wind turbine parts – timely replacement of parts such as generators, blades, and control systems
- Monitoring wind turbines – using monitoring systems to detect performance and faults before they become major issues,
- Scheduled maintenance – includes oil changes, inspections, and repairs,
- Troubleshooting faults – determining cause of faults, damages, or issues
- Data analysis – analyze performance data to identify potential problems,
- Training of personnel – understand maintenance process[34]

2.5.1 Pacific Northwest National Laboratory's Maintenance Best Practices

PNNL discusses the importance of both preventive and predictive maintenance for wind turbines. Preventive maintenance is performed by a contracted maintenance service provider but can be done by in-house staff with the proper training. Predictive maintenance involves evaluating the turbine through periodic and continuous condition monitoring to estimate the best time for maintenance to be done to prevent failures.[35] Having a continuous condition monitoring system integrated on a turbine, means that operating data is continuously collected, and maintenance is performed based on the actual condition of the turbine, which is more cost-effective. Manufacturer warranties usually cover 2-5 years but can be extended to 5-10 years and they go into effect upon installation of the turbine. Often an O&M agreement with a maintenance contractor is recommended so the manufacturer's maintenance schedule can be adhered to.[36]

PNNL also provides an example of a maintenance checklist here, which would be used on an annual basis. The checklist would not supersede the maintenance recommendations from the equipment manufacturers or contracted O&M or warranty services.

2.5.2 Current Maintenance Process

Current maintenance processes include wind technicians climbing the wind turbine to fix any issues that arise. The technicians typically carry about 45 pounds of gear and tools and can take 20 minutes to reach the nacelle. The technicians troubleshoot and repair the electronics and mechanics to keep the blades spinning, and each technician is required to complete a two-year technical program to achieve certification and 50 hours of training. With additional training technicians can also use drones to help make the inspection process easier and safer.[37]

Maintenance activities for offshore wind turbines are typically performed by rope-access technicians. Challenges include working in extreme conditions and are based on favorable weather conditions, and the use of crew transfer vessels (CTVs) and service operation vessels (SOVs) to transfer the crews to the turbines make up a significant portion of the wind farm maintenance costs.[38]

2.6. Cost Comparison Current Practices vs. Autonomous Tools

Various studies have been conducted to evaluate the cost savings of using autonomous tools for wind turbine inspection vs. the current practices of using technicians for physical inspection and repair activities.

2.6.1 UK Study of Drone-Based Inspection Levelized Cost for Offshore Wind

A study conducted by Khristopher Kabbabe Poleo and his colleagues in 2021 presented a physical and financial model which addressed the benefits of using drones for inspection and maintenance. Rope-access inspection is used as a baseline and accounts for 0.7% of offshore wind farm operational expenditure. According to this study using drones can reduce the costs by up to 70% and decrease revenue lost due to down-time by up to 90%. Increasing autonomy of drones increases the speed of inspections but increases costs and complexity. For the wind farm operator, there is a 2% reduction in inspection costs.[39] The tables and figures in this report provide detailed information in pounds of the cost for inspecting an offshore wind farm in the UK using drone-based inspection.

2.6.2 Canadian Cost Comparison

Recon Aerial, a Canadian company which provides drone wind turbine inspections provides information on its website regarding the estimated cost of rope inspection in contrast to its drone inspection service. “The total cost of both the rope inspection and the lost energy production is approximately **$3,525**. (10hrs, $0.10 per kWh, a capacity factor of 35%, and a nameplate capacity of 1500 kWh). Using drone wind turbine inspections through Recon Aerial takes about 45 minutes of total downtime ($42) and costs approximately $769 per wind turbine.”[40]

2.7. Offshore Wind Farms

Offshore wind farms include both fixed support and floating turbines. Floating offshore wind farms are gaining in popularity as their potential installation locations provide the opportunity to capture stronger winds and build out larger farms. The operation and maintenance activities associated with floating offshore wind involve inspection and maintenance of components of the turbines and their subsystems and are typically performed by technicians with the rope access technique. The O&M scope includes performing preventive and corrective maintenance, inspection, surveys, and condition monitoring; all of these are usually included in the O&M contracts for wind farm operations. There are maintenance activities specific to the floating aspect of the wind turbines and these include maintaining the floating platforms, mooring lines, anchors, and dynamic cables. Annual surveys are needed to assess the condition of caternary moorings and drag anchors. Dynamic cables require regular visual inspection, and the floating platforms need to be inspected for weather related cracks and damage. Challenges specific to floating wind farm inspection and maintenance include the increased cyclic loads that floating turbines are subjected to because of the wind and waves and are therefore more prone to structural damage. The mooring lines are also exposed to harsher conditions and the inspection and maintenance activities need to be done more often. The repair tasks can be more time consuming and more complex because of the floating foundations.[41]

The turbine operation and maintenance activities include both preventive and corrective maintenance. Preventive is calendar based with a fixed number of inspections conducted irrespective of actual damage or condition based where a repair is done based on observations of potential defects on the turbine. Corrective maintenance can be deferred until there is expected to be a failure and then the repair is done to prevent it, or immediately upon failure.[42]

2.7.1 Robotics Used for O&M

The trends in research for robotics in offshore floating wind farms include the types of mobility, sensing capabilities, size and weight, and levels of autonomy. Mobility involves the motion of the robot in unstructured environments to efficiently capture data. The thruster technology of a subsea robot needs to be controllable and efficient while minimizing the possibility of a crash. Subsea robots need a better operational range to be able to conduct longer monitoring activities. The robot should be able to steer itself and maneuver to the required asset. The dexterity of a manipulator arm of a climbing robot is key. Sensing capabilities refer to the sensors that aid in navigation and control and determine the robot's operational capability for inspection. The size of the robot needs to be able to accommodate the sensors and manipulators. The robot needs to be light in weight but also carry the necessary payload. The level of autonomy refers to the automation capability of the robot. Different autonomy levels can be used for different tasks and the trend is towards more fully autonomous tools and systems.[43] The figure below illustrates the types of sensors needed for control, operation, and maintenance.

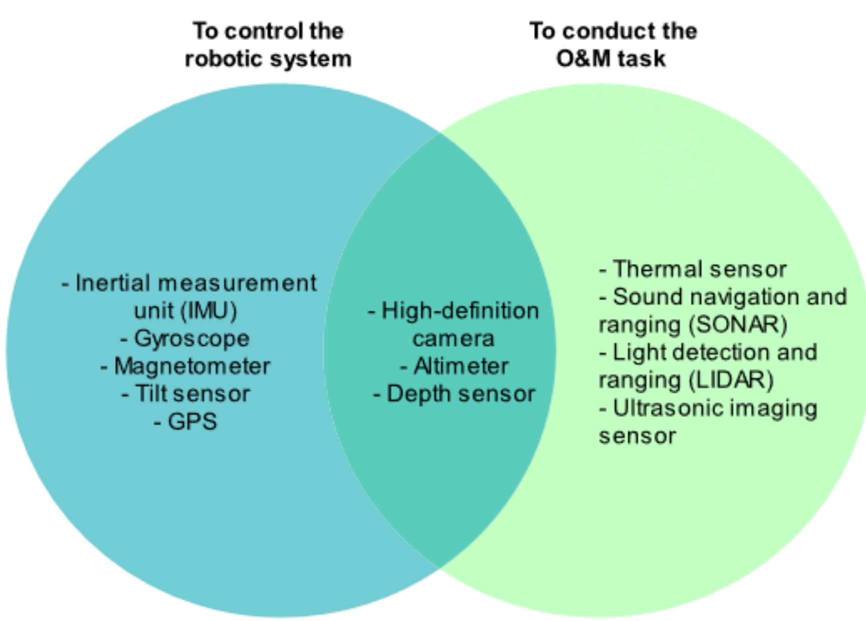

Figure 7: Sensors Needed to for Typical O&M Tasks for Robotic Systems
Source: Wind Energy, 2022[44]

2.7.2 Climbing Robots

Climbing robots are being positioned to take over tasks such as cleaning blades and inspecting structural defects, which is usually done by rope access technicians. Climbing robots are classified as:

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 and four 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.[45]

Figure 8: Robotic Wind Turbine Blade Cleaning from Dust and Oil

Source: Click here to see video

2.7.3 Unmanned Aerial Vehicles

In the case of floating offshore wind farms (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 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.[46]

2.7.4 Subsea Robots

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.[47]

Figure 9: The Atlantis Testing Platform for Maritime Robotics

Source: Click here to see video

Table 2: 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

Source: Wind Energy, 2022[48]

2.7.5 Underwater Drone Inspections

Researchers have modified a remotely operated vehicle to conduct autonomous underwater inspections of wind farm foundations. The research team is from the Offshore Robotics for Certification Assets (ORCA) Hub, and they partnered with the energy company, EDF Renewables, to deploy their ROV to the inspection of EDF's Blyth Offshore Wind Farm in England. The ROV includes robotic technologies for autonomous inspections and conducts visual inspections of the foundations of offshore wind turbines. This trial allowed for exploring the drone's ability to autonomously record videos to assess the exterior condition of turbine foundations and cables. The drone was equipped with sensors and cameras to capture and create 3D models of parts of the underwater assets used to monitor biofouling on the foundations.[49]

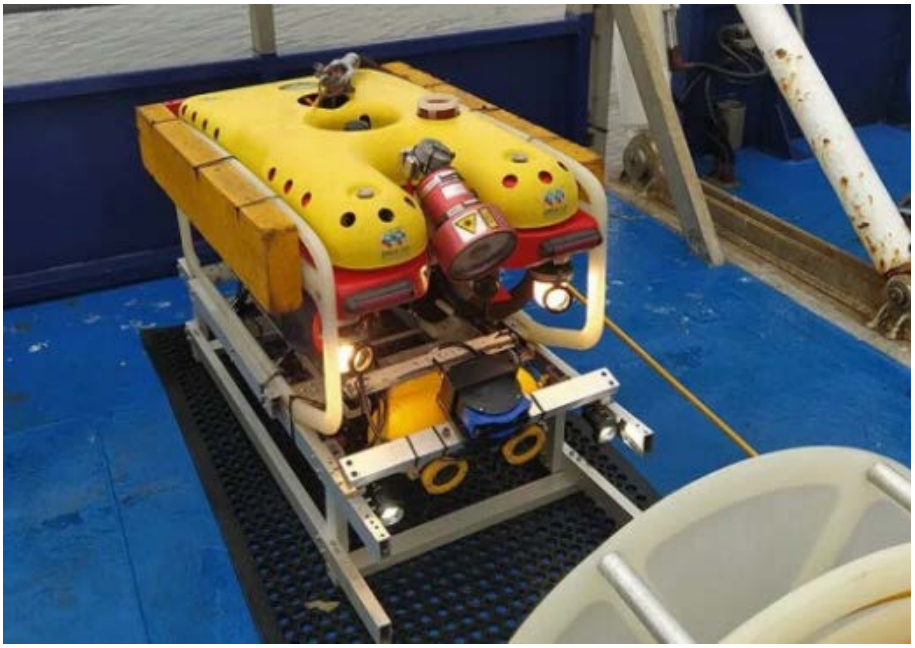

Figure 10: Underwater Drone for Wind Farm Foundation Inspections
Source: Journal of Petroleum Technology, 2022[50]

Another project, funded by the EU called ATLANTIS, is using underwater robots to scan the base of offshore wind turbines for signs of damage. This activity is part of the goal to reduce inspection costs. Using robots for inspection also reduces the risk to technicians who would have to be transferred from boats to the turbines and then dive down to inspect the foundations. The project's base site is an offshore wind farm in the Atlantic Ocean off the coast of Portugal.[51]

3.0 Autonomous Tools for Installation, Inspection, Operations & Maintenance

This section explores the different autonomous tools, baseline practices, and processes being increasingly used for wind turbine maintenance.

3.1. Drone Technology

Unmanned aerial drones come in three categories: multirotor, fixed-wing, and single-rotor helicopters. Multirotor consists of either three, four, six, or eight rotors. The four-rotor drone is the most popular and widely used and is also the cheapest. They can fly for only 20 to 30 minutes at a time as they require a lot of energy to operate. The fixed-wing drone has one rigid wing to provide the lift rather than vertical lift rotors. Fixed-wing drones need less energy to stay in the air and are therefore more efficient than the multirotor. Single-rotor drones have one rotor and a tail rotor which controls their heading. They are able to hover with a heavy payload, however they are complex devices, and their spinning blades could be dangerous.[52] The different drone technologies are included below with their advantages and disadvantages highlighted.

Table 3: Advantages and Disadvantages of Multirotor, Fixed Wing, and Single-rotor Drones

Type of Drone	Advantages	Disadvantages
Multirotor	• Low Price • High accessibility • Great maneuverability • Ease of use • Vertical take-off and landing (VTOL) • Good camera control	• Short flight times • Small payload capacity • Low stability in the wind
Fixed-wing	• Long Endurance • Large area coverage • Fast flight speed • Great stability • Safer recovery form motor power loss	• High price • Large take-off/landing zone is required • No VTOL/hover • Challenging to fly; training is needed • Low efficient for area mapping
Single-rotor	• Long Endurance • VTOL and hover flight • High payload	• High price • Dangerous • Difficult to fly; training is needed

Source: Robotics, 2021[53]

3.1.1 Robot Technology

Different inspection robots use different technologies for the actual inspection tasks – from high-precision video cameras for external, visual inspection to ultrasonic or infrared arrays that allow subsurface defects to be detected. Robotic inspection technologies can even include an 'electronic skin' to "feel" the surface of a blade and collect data on the surface structure. Aside from inspection, these robots can also be used to carry out basic maintenance tasks, such as cleaning and resurfacing the blades. The methods used to deploy and move the robot across the blade differ between different designs, but generally use either a legged crawling design or a tracked or wheeled design. BladeBUG, for example, is a six-legged robot invented by entrepreneur Chris Cieslak (pictured below). The robot uses suction cups on its feet to attach itself to wind turbine blades. These cups can change shape as the crawler moves along the blade with a camera allowing the operator to see what is happening as they control it with a gaming controller. These robots can also be deployed at offshore wind farms using drones.[54]

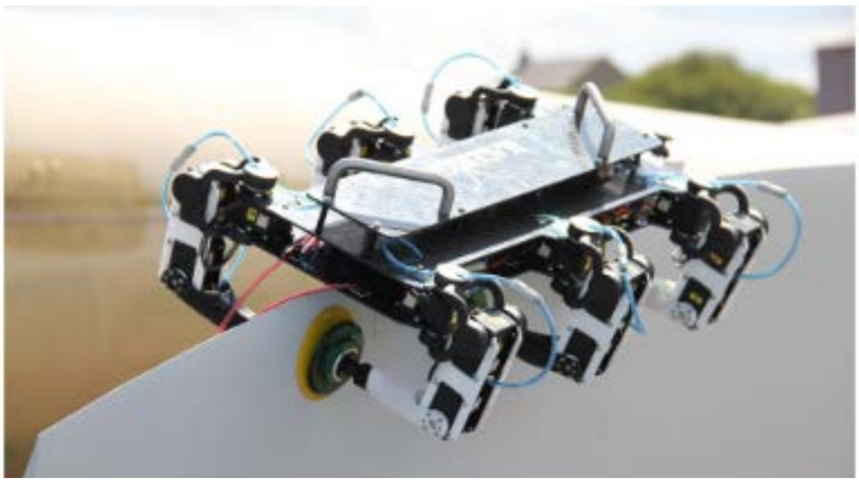

Figure 11: BladeBug MKII IMR Robot
Source: Journal of Field Robotics, 2022[55]

The International Climbing Machine, by contrast, is a remote-controlled tank-like robot that can withstand high winds and successfully navigate over bolts and other obstacles. It uses an on-board vacuum suction system to create a seal as the caterpillar tracks drive it along the surface of the structure.[56]

Figure 12: International Climbing Machine – Suction Held Robot
Source: International Climbing Machines, 2023[57]

The Innovate UK-funded MIMRee (Multi-Platform Inspection, Maintenance and Repair in Extreme Environments) project is an example of various technologies coming together to aid wind turbine inspection. This project used an unmanned vessel, drone, and crawling robot to create a complete system for transporting, deploying and retrieving a blade crawling robot as well as carrying out visual inspection via drone. Once the drone has been used for a preliminary inspection it can return to the unmanned vessel to pick up the crawling robot and place it on the turbine blade for a closer inspection such as high-resolution imaging and non-destructive sensing, including ultrasound.[58]

3.1.2 Robotics and AI for Installation

Robotics and AI used for the installation of wind turbines are still in the developmental stage. Challenges exist in creating autonomous systems that are large and powerful enough to transfer heavy components into their positions and to support structures in changing weather conditions and follow safety procedures. Commercial off the shelf and novel robotics provide opportunities for operations in all seasons and the lowered risk for offshore personnel and less human intervention.[59]

Operational support remains a large proportion of a wind farm and represents not only visual aspects such as the wind turbine, but also subsea cables, foundations, substation and cables on land which connect to the national grid. O&M of subsea cables represents a large barrier for offshore engineers as it can be a difficult area to inspect due to high currents, deep waters and volatile weather conditions. Therefore, novel sensing mechanisms can be utilized as payloads on surface and subsurface vessels track subsea cable positions and the health of these assets. External condition monitoring utilizes a visual observation of the external integrity and position of the cable on the seabed (unburied, buried, strumming). Robotic platforms have the ability to reduce risk for personnel as they can operate under different conditions that the seabed is inherent to. Novel sensing mechanisms can be used to evaluate the integrity of the cables to ensure a resilient energy supply and in some cases use AI for predictive maintenance for optimal performance.[60]

3.1.3 Technology for Nacelle Inspection

One of the platforms that can be used for the internal inspection of the nacelle structures in offshore wind turbines, is a robot that travels on a permanently installed rail system within the nacelle structure. Benefits of this platform include safe travel on a predetermined route preventing damage to any equipment and the inclusion of suites of sensors, such as infrared detection or friction or faculty electrical systems, microphones and other sensors for vibration and temperature. Some of the challenges include that it requires early adoption so the designs can be integrated by the manufacturer, lack of manuverability means faults in hard to reach areas can go undetected, and it only covers certain elements.[61]

3.2. Sample List of Companies in the Wind Turbine Drone Market

This section provides an overview of the landscape of companies that are developing drones for the wind turbine market. Both global and U.S. companies are included and information on their drone products is provided.

3.2.1 Flyability

Flyability is a Swiss company building drones for operating in complex and confusing spaces. According to Zoominfo, Flyability's revenue is $27.2 million. One of their drones, Elios 3, can be used in wind turbine inspection.

Flyability's Elios 3 (image below) is an indoor drone that can navigate the chambers of wind turbine blades and quickly retrieve high-resolution imagery and data. The steps to performing an internal wind turbine inspection with the drone are as follows:

1. Equip drone with UNISET devices for drone location within the blade.
2. Pilot enters the manhole, giving access to the chamber that holds the blades.
3. The drone is then flown down into each blade, collecting visual data.[62]

Figure 13: Elios 3
Source: Flyability, 2023[63]

3.2.2 Aerones

Aerones, headquartered in San Jose, California, provides robot-enabled wind turbine maintenance and inspections services. According to Zoominfo, Aerones' revenue is $22.9 million. The base platform of the Aerones Wind Turbine Leading Edge Repair Robot is the modular toolkit, which is a winch system that allows controls for both vertical and horizontal spaces. Different robotic arms can be attached for various maintenance and inspection functions. The robots use ultrasound scanning and cameras to examine and repair the blades.[64] A video is included to demonstrate how the robot moves around the blade and its different cleaning capabilities.

Figure 14: Aerones Robotic Wind Turbine Blade & Tower Cleaning
Source: Click here to see video

3.2.3 Rope Robotics

Rope Robotics is a Denmark-based company that is developing robotic wind turbine blade repair and maintenance solutions. According to ZoomInfo, Rope Robotics' revenue is less than $5 million. The robot is attached to ropes and hoisted from the ground onto the damaged blade and attaches itself with a vacuum system, while motors allow the robot to move across the blade. It has an onboard high-resolution camera and laser scanner so that it can inspect the surface and detect any damage and then can initiate the repair process.[65] A video from the company is included below which demonstrates the process.

Figure 15: Rope Robotics LEP Solution
Source: Click here to see video

3.2.4 Cyberhawk

Cyberhawk, with a presence in Littleton, Colorado, Edinburgh, United Kingdom, and Doha, Qatar, provides visual data solutions using drones and data management and analytics software for power grid operators. A 2022 article lists the company's revenue as growing from $13.5 million to $22 million. Along with a strong focus in the US, the company is gaining traction in the Middle East, where it's drone and data-visualization solutions are used in construction projects.[66] For the wind sector, Cyberhawk provides drone-based inspection and data management services. Their drone service provides close visual inspection of an entire wind turbine, cooling tower, or chimney stack. The data processing services include analyzing the data collected and reporting on the size and location of the defects. iHawk, the cloud-based visual assessment management software, delivers inspection results to operators and OEMs to understand the condition of the asset.[67]

3.2.5 SkySpecs

SkySpecs, headquartered in Ann Arbor, Michigan, provides autonomous drones for turbine blade inspections. The company claims to monitor the health of nearly half of all turbine blades in North America and have inspected more than 300,000 blades across the globe.[68] According to Zoominfo, SkySpecs' revenue is $36.6 million. Their drones use AI analysis and machine learning tools to provide a detailed analysis of inspections in SkySpecs blade asset management platform called Horizon. The Horizon platform provides customers with data and insights to manage the health of assets, identify blade trends, and optimize O&M planning.[69]

SkySpecs' drone technology includes capturing geospatial image metadata, 3D Lidar scanning, in-flight photography controls, sun avoidance software, and advanced autonomous flight controls to enable inspections in windy conditions. The drones can provide inspections in an average of 15 minutes and rapid notification of high severity damages. SkySpecs services encompass full-time pilots, a team of industry experts and blade engineers to help analyze the data, and a global database of blades data to understand trends and risks.[70]

Figure 16: SkySpecs Drone Inspecting a Turbine
Source: SkySpecs, 2023[71]

3.2.6 Clobotics

Clobotics, headquartered in Bellevue, Washington, provides autonomous blade inspections for wind turbines. For their onshore services, Clobotics offers blade inspections using the autonomous Clobotics IBIS drone-based system for inspecting the blades and the data collected can be accessed, viewed, and generated into reports using the online portal. According to Zoominfo, Clobotics' revenue is $22.9 million. The offshore services include a customized project according to local settings, regulations, weather forecasts, and asset brand and type. Clobotics performs the inspections using the client's own vessels or charter suitable vessels to launch the drones which means a high cycle time and safer operation with no technician needed to transfer to the turbine.[72]

Clobotics' business model is a Drone as a Service (DaaS) partnership where a technician trained by Clobotics will perform the inspections and upload the data. The company will have access to the data to comment on or share with relevant stakeholders. The training of the technician and engineers is a 2-day training on inspections, maintaining equipment, and delivering data.[73]

Clobotics performs internal blade inspections with blade specialists who are trained in using advanced robot crawler systems. The ROV is used to inspect the blade tip and the highly experienced Clobotics project management team facilities the project.[74] A detailed overview of roles the crews provided play and the sequence of steps are discussed in detail in their literature.

3.2.1 Action Drone

Action Drone is a drone solutions company that helps research, develop, and manufacture small unmanned aerial systems according to customer needs. One of their areas of industry focus is wind turbine inspections. With Action Drone's automated drones, inspections can be done on an average of 18 turbines in a day. Action Drone's drone teams do the inspection work in a matter of days or weeks.[75] The following video gives a visual idea of the autonomous drone inspections that can be done by Action Drone.

Figure 17: Wind Turbine Inspection Services with Autonomous Drones
Source: Click here to see video

3.2.2 VideoRay

VideoRay, headquartered in Pottstown, Pennsylvania, provides ROVs for a variety of industries and applications. One of those applications is for wind turbine installations and offshore wind turbine inspections. Orsted and DEME Offshore are both listed as customers who are using VideoRay's ROVs for offshore inspections.[76] According to a news article released by the company in 2022, their revenue growth has grown approximately 45% over 2021, with a three-year annual growth of more than 30% per annum. Their annual revenue exceeds $30 million.[77] The company's Mission Specialist series ROVs can be used to help reduce the cost of maintaining offshore wind farms. The submersibles can perform thorough underwater inspections without the need for human divers.[78]

3.2.3 Mile High Drones

Mile High Drones offers photo and video aerial services in drone services for a variety of industries and applications. Their services for the solar and wind industry include drones for inspections and damage assessment. Mile High Drones can be used to capture high-resolution images and 4K videos, which can then be zoomed in on to detect any faults. Thermal imagery FLIR cameras are used to detect energy loss and performance issues.[79]

3.2.4 ABJ Renewables

ABJ Renewables provides drone and proprietary inspection solutions to the renewable energy industry. Their ABJ WindVue Wind Farm Inspection system uses intelligent drone inspection technology with thermal imaging to detect issues as small as 3mm.[80]

The Intelligent Blade Inspection Technology utilizes the wind turbine blade heating and cooling at different rates. The drones use infrared cameras to measure the small differences and gather information in an efficient manner so that the turbine does not have to be down for long periods of time.[81] The issues that can be identified by ABJ Renewables technology include:

- Internal damages
- Delamination
- Bad bonding
- Resin gaps
- Core defects

- Lightning strike / Flashover
- Balancing material problems[82]

3.3. Best Practices

In order to conduct thorough inspections using UAVs, best practices include developing a comprehensive inspection plan which includes all parts of the turbine, using multiple inspection techniques and tools to get a complete understanding of the condition of the turbine, schedule regular inspections, utilize software to analyze and organize the collected data, and coordinate with maintenance teams to address any issues.[83] For the safe operation of UAV's the following best practices should be used:

- Maintain regular communication with local aviation authorities,
- Have well-trained drone operators who understand regulations and guidelines,
- Have a risk assessment and safety plan to address potential hazards,
- Have regular equipment checks to ensure UAV parts are in working order,
- Establish clear protocols for emergency situations including weather and equipment failure[84]

3.3.1 FAA Regulations for Drone Operation

The FAA has regulations for drone operations for unmanned aircraft systems. The following are the operating requirements:

- Always avoid manned aircraft.
- Never operate in a careless or reckless manner.
- Keep your drone within sight. If you use First Person View or similar technology, you must have a visual observer always keep your drone within unaided sight (for example, no binoculars).
- You cannot be a pilot or visual observer for more than one drone operation at a time.
- Do not fly a drone over people unless they are directly participating in the operation.
- Do not operate your drone from a moving aircraft.
- Do not operate your drone from a moving vehicle unless you are flying your drone over a sparsely populated area and it does not involve the transportation of property for compensation or hire.[85] In addition to these

operating requirements, drone operators will need to register each drone, obtain a pilot certification, and drone certification.

4.0 Drone Inspection and Monitoring Market

An overview of the drone inspection and monitoring market is included in order to better understand the needs, trends, and drivers for drone inspection in the wind turbine sector. This information comes from a 2023 MarketsandMarkets report entitled "Drone Inspection and Monitoring Market (Global Forecast to 2027). There are various applications for drones in the inspection and monitoring sector. The timeliness and accuracy of drones as well as their reasonable prices are leading to their adoption. The application areas include construction& infrastructure, agriculture, oil & gas, utilities, mining, and others (logistics, wildlife & forestry, insurance, and aviation-related drone inspection and monitoring).[86] **Wind turbine inspection falls under the utilities category,** along with tower inspection and power transmission.

4.1. Drone Inspection and Monitoring, by Application

Today, drone inspection globally is used primarily in the construction and Infrastructure segments and agriculture. In fact, the use of drone inspection in the utilities sector is the smallest.

Table 4: Global Drone Inspection and Monitoring Market, by Application, 2022-2027 (USD Million)

Application	2022	2023	2024	2025	2026	2027	CAGR (2022–2027)
Construction & Infrastructure	2,501.24	3,120.34	3,148.15	4,015.93	4,058.96	5,313.59	16.3%
Agriculture	2,610.17	3,078.83	3,088.55	3,674.31	3,687.70	4,431.99	11.2%
Oil& Gas	796.14	971.27	977.13	1,210.97	1,219.00	1,537.64	14.1%
Utilities	188.08	217.26	218.33	255.50	257.07	305.45	10.2%
Mining	276.12	311.69	312.46	355.52	356.63	409.75	8.2%
Others	580.84	640.64	641.90	711.34	712.90	794.28	6.5%
Total	**6,952.61**	**8,340.03**	**8,386.51**	**10,223.57**	**10,292.25**	**12,792.70**	**13.0%**

Source: Reprinted with Permission from MarketsandMarkets, 2023[87]

The data for the U.S. shows a different pattern with agriculture being largest sector that has adopted the use of drones for monitoring and inspection. Use of UAVs in the utilities sector still lags behind.

Table 5: U.S.: Drone Inspection and Monitoring Market, by Application, 2022-2027 (USD Million)

Application	2022	2023	2024	2025	2026	2027	CAGR (2022-2027)
Construction & Infrastructure	451.89	511.66	511.73	579.58	579.66	656.69	7.8%
Agriculture	1,809.60	2,088.55	2,092.32	2,423.62	2,428.09	2,823.02	9.3%
Utilities	112.64	125.07	125.19	139.26	139.39	155.36	6.6%
Oil & Gas	60.50	66.30	66.44	73.18	73.42	81.41	6.1%
Mining	154.34	167.32	167.30	181.31	181.28	196.40	4.9%
Others	225.91	242.09	241.98	259.09	258.98	277.05	4.2%
Total	**2,814.88**	**3,200.99**	**3,204.96**	**3,656.05**	**3,660.83**	**4,189.94**	**8.3%**

Source: Reprinted with Permission from MarketsandMarkets, 2023[88]

This report also provides data on the global drone inspection and monitoring market by utilities. Although the wind turbine application is still the smallest, the forecast sees the global market for this sector doubling by 2027.

Table 6: Global Drone Inspection and Monitoring Market, by Utilities, 2022-2027 (USD Million)

Utilities	2022	2023	2024	2025	2026	2027	CAGR (2022-2027)
Tower Inspection	481.67	588.34	589.16	731.51	732.93	926.80	14.0%
Power Transmission	191.88	232.00	234.22	287.46	290.37	362.47	13.6%
Wind Turbines	122.59	150.93	153.75	192.01	195.71	248.36	15.2%
Total	**796.14**	**971.27**	**977.13**	**1,210.97**	**1,219.00**	**1,537.64**	**14.1%**

Source: Reprinted with Permission from MarketsandMarkets, 2023[89]

North America includes three regions, the U.S., Canada, and Mexico. The following forecast reflects that application in the wind turbine market is still small but growing.

Table 7: North America: Drone Inspection and Monitoring Market, by Utilities Application, 2022-2027 (USD Million)

Application	2022	2023	2024	2025	2026	2027	CAGR (2022-2027)
Tower Inspection	53.87	59.42	58.97	65.14	64.62	71.48	5.8%
Power Transmission	43.68	48.79	49.04	54.86	55.14	61.80	7.2%
Wind Turbine	20.03	22.57	22.89	25.84	26.20	29.63	8.1%
Total	**117.59**	**130.78**	**130.89**	**145.84**	**145.96**	**162.92**	**6.7%**

Source: Reprinted with Permission from MarketsandMarkets, 2023[90]

4.2. Drone Inspection and Monitoring, by Solution

The solution market is segmented into platform, software, infrastructure, and services. The platform segment includes airframe, avionics, propulsion, software, and payload. The software segment includes route planning and optimization, inventory management, live tracking, fleet management, and computer vision & object detection. The infrastructure segment includes ground control stations, charging stations, and launch & recovery systems. The services segment includes drone platform services such as flights operations, data analysis, and data processing.[91] In the U.S. the drone inspection and monitoring services market is the largest. It is important to keep in mind that this is across all applications (agriculture, construction, oil, and gas, etc.).

Table 8: U.S.: Drone Inspection and Monitoring Market, by Solution, 2022-2027 (USD Million)

Solution	2022	2023	2024	2025	2026	2027	CAGR (2022-2027)
Platform	1,173.14	1,339.58	1,576.97	1,885.43	2,284.32	2,577.12	17.0%
Software	246.51	270.21	303.34	345.97	402.74	472.95	13.9%
Infrastructure	274.98	312.37	365.82	435.11	524.44	588.61	16.4%
Services	2,814.88	3,200.99	3,204.96	3,656.05	3,660.83	4,189.94	8.3%
Total	**4,509.52**	**5,123.14**	**5,451.08**	**6,322.56**	**6,872.33**	**7,828.62**	**11.7%**

Source: Reprinted with Permission from MarketsandMarkets, 2023[92]

Growth Opportunities and Restraints

Drones are being used for close, 36-degree inspections and collecting data, which can be done in weeks instead of months. They are also being used to transport tools and equipment to technicians at the top of the turbines. They are outfitted with cameras, light detection and ranging (LiDAR) to inspect the turbines for cracks, erosion, and other potential flaws to perform repairs before major damage occurs. It is noted that drones with high wind resistance and magnetic interference are needed for the high wind speeds associated with inspecting turbines.[93]

Drones require a skilled pilot and there is an insufficient number especially in developing countries. Another constraint is security. UAVs are susceptible to numerous threats and vulnerabilities including susceptibility to spoofing and malware infection, theft and manipulation, technical issues, and Wi-Fi jamming. The technical issues include connection breakdown between the user's device and the drone, lack of reliable connections, short battery life and short flight times.

5.0 Summary and Conclusions

This report explored the role that drones and robotics increasingly play with wind turbine operations and maintenance. Recognizing that the lifespan of both land-based and offshore wind turbines can be extended by monitoring performance and implementing the correct maintenance procedures, it is important for this industry to find the best method(s) for accomplishing this goal, as the number and size of wind turbines continues to grow. Numerous examples of drones and robotic solutions were presented. Most of these required teams of wind tecs, drone pilots, and unmanned devices working together in complex environments. Data on the drone inspection market was included which show that globally the principal applications are with construction and agriculture. Drone inspection of wind turbines is considered part of the utilities segment and is one of the smallest applications both globally and domestically. Security issues need to be considered with the use of drones as they are prone to cybersecurity issues. For this reason some vendors, such as Parrot Anafi are developing secure drones.

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