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WIND ENERGY SCIENCE DISCUSSIONS

A Survey on Applications of Small Uncrewed Aircraft Systems for Offshore Wind Farms

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Abstract.

Offshore wind farms are attractive energy sources due to the abundancy of wind resources close to population centers. Nevertheless, offshore locations present unique challenges for atmospheric observation and turbine inspection which are essential for wind farm design and maintenance. Small uncrewed aircraft systems (sUAS) are well suited for solving many difficulties inherent to offshore sites. In the past decade, sUAS have risen as a versatile and cost-effective platform for a large variety of scientific and commercial operations relating to atmospheric observation and infrastructure inspection. Most sUAS fall into one of two classes: fixed-wing or rotorcraft. Fixed-wing aircraft offer high endurance and range at the cost of constrained maneuverability. Rotorcraft are agile and user-friendly platforms, but offer limited endurance. We present a survey on the challenges and opportunities of utilizing fixed-wing and rotorcraft sUAS for wind resource assessment, operational observation, and inspection of offshore wind farms.

1 Introduction

In recent decades, advances in offshore wind energy technology have made the development of commercial wind farms economically advantageous. Coastal wind farms are attractive in part due to the abundant availability of wind resources close to population centers (Bodini et al., 2019). In 2020, installed global offshore wind farm capacity reached 18 GW out of 733 GW of global wind farm capacity (Díaz and Soares, 2020; Jung and Schindler, 2022). In 2022, North American installed offshore wind farm capacity reached 42 MW, out of 136 GW of wind farm capacity (Musial et al., 2022; Wiser et al., 2022). Scientists estimate that available U.S. offshore wind energy is almost twice the U.S. current electrical consumption of 4000 TWh per year (U.S. Energy Information Administration, 2023; Bodini et al., 2019).

Unlike onshore wind turbines, which must account for road and rail transportation constraints, offshore turbines are built in harbors and transported by boat to construction sites. Therefore, offshore turbine blades can be twice as long and generate more than four times as much power than onshore turbines (Hartman, 2022). Despite these benefits, development of offshore wind farms is not without its challenges. This paper focuses on the challenges pertaining to atmospheric measurement, operational observation, and maintenance related inspection for offshore wind farms.

During the planning phase of any wind farm, a thorough wind resource assessment must be conducted. This involves measuring or estimating on-site winds over the course of at least one year (Probst and Cárdenas, 2010; Murthy and Rahi, 2017;

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Emeis, 2012; Brower, 2012). Standard wind measurements are made using a combination of anemometers (cup, prop, sonic), light detecting and ranging (lidar), scatterometers (SCATs) and synthetic aperture radar (SAR) satellite data.

In-situ measurements are desirable because of their accuracy and high temporal resolution – for example, anemometers can generally measure wind within 0.1 m/s at a frequency of 0.5 to 1 Hz (Brower, 2012). However, installation of meteorological masts offshore can cost over 10 million USD (Russell, 2017; Kim and Lim, 2017) and towers require regular maintenance (Somayaji et al., 2008). Furthermore, the horizontal spatial resolution is limited to a single location per tower.

Conversely, satellite methods like SCATs and SAR measurements offer a higher horizontal spatial resolution with lower temporal resolution. Satellites use semi-empirical methods to estimate surface winds (Brower, 2012). Neutral stability is a common assumption made for extrapolating surface winds to hub height. This assumption breaks down when there are variations in wind shear, resulting in large uncertainties for wind speed estimates at hub height (up to 3 m/s) (Hasager et al., 2020). Machine learning has been shown to improve extrapolation models to mitigate this error (Optis et al., 2021).

Lidar have become a common tool for offshore wind measurements due to their smaller size and affordability (Viselli et al., 2019; Hsuan et al., 2014). To measure winds offshore, lidar are fixed to buoys and placed in locations of interest. Lidar take accurate measurements with high temporal resolution and can be deployed at multiple sites to improve spatial resolution (Brower, 2012). Wind speed and direction measurements from offshore lidar are accurate to within 0.1 m/s and 5 degrees (Viselli et al., 2019). Because of its advantages, use of lidar is expected to continue to grow (Brower, 2012).

Measurement challenges persist once offshore wind farms are constructed as atmospheric measurement is critical for accurate evaluation of wind farm efficiency and productivity. Subsequent analysis provides valuable information which can inform the design and implementation of future wind farm projects.

Maintenance becomes a priority upon the completion of any construction. This is especially true for offshore structures like meteorological towers and wind turbines which must endure dynamic and corrosive environments. Meteorological towers require either annual or biannual comprehensive inspections of every component – including sensors, data acquisition systems, communications systems, aviation warning lights, safety cables and more (Mohler and Faith, 2021). This work requires specialists to physically inspect the tower and perform repairs (Mohler and Faith, 2021). The National Renewable Energy Lab (NREL) estimates that installation, operation and maintenance account for about a third of offshore wind farm costs (Maples et al., 2013). To inspect wind turbines, two to three technicians will typically travel two hours from harbor by workboat – alternatively, a helicopter can be used to reduce travel time. Once at the site, inspection of the platform, tower, hub and each blade can take 6-10 hours (Maples et al., 2013). If conditions are poor (e.g. significant wave height greater than 0.9 m or winds greater than 12 m/s (Maples et al., 2013)), the inspection process can take multiple days.

Small Uncrewed Aircraft Systems (sUAS) have potential to augment current atmospheric observation and inspection methodologies. sUAS equipped with sensors can make additional in-situ measurements to improve observational records constructed from anemometer, lidar, and satellite data. For example, the mobility of sUAS could allow for coordinated measurement with satellites, as targeted measurement could provide atmospheric stability information to improve extrapolation models. sUAS also offer new capabilities for observation around installed wind turbines. In-situ measurements from sUAS are already being incorporated into studies around wind turbine wakes in the American WAKE Experiment (AWAKEN) (Herges et al., 2020).

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Beyond atmospheric measurement, sUAS can help with assessing wind turbine health. Studies have already shown that sUAS carrying infrared camera payloads have the ability to detect cracks (Galleguillos et al., 2015) and ice build up (Gao and Hu, 2021) on turbine blades.

This paper presents a survey of the current capabilities and limitations of fixed-wing and rotorcraft sUAS and discusses potential applications relevant to offshore wind energy, in particular wind resource assessment, operational observation and inspection.

2 Small Uncrewed Aircraft Systems

The United States Federal Aviation Administration defines Small Unmanned Aircraft Systems (sUAS) as aircraft weighing less than 55 lbs (24.95 kg) on takeoff[1]. Also colloquially known as Small Uncrewed Aircraft Systems, drones, or remotely piloted aircraft systems (RPAS), this class of aircraft have emerged as a cost-effective tool for targeted information gathering in low-altitude applications.

2.1 Classes of sUAS

Small uncrewed aircraft are composed of two primary classes: rotorcraft and fixed-wing aircraft. Other platforms such as fixed-wing vertical takeoff and landing (VTOL) aircraft exist but are more complex and less ubiquitous. We therefore focus this survey on rotorcraft and fixed-wing sUAS (Table 1, Figures 2, 3).

Rotorcraft are versatile, maneuverable, and user-friendly platforms that can accommodate various payloads. They are popular for aerial robotics, as they can be flown with precision in compact indoor environments. Common applications for rotorcraft include infrastructure inspection (Nordin et al., 2022; Poleo et al., 2021; Shafiee et al., 2021), search-and-rescue (Ray et al., 2022), and small-scale surveying (Kellner et al., 2019). Because rotorcraft sUAS produce nearly all their lift force via propellers typically driven by electric motors, the payload, endurance, cruise speed, and range are relatively limited compared to fixed-wing sUAS. While these problems may be improved by minimizing aircraft weight and utilizing high-density fuel (such as petroleum or hydrogen), the inherent aerodynamic inefficiencies provide a challenge when compared to a fixed-wing of similar propulsion configuration.

Fixed-wing aircraft are a popular alternative to rotorcraft, especially for missions which require relatively longer endurance, higher airspeeds, and larger payloads. As such, common applications of fixed-wing sUAS include long-duration atmospheric boundary layer monitoring (Oettershagen et al., 2017), severe-storm sampling (Elston et al., 2011; Frew et al., 2020), large-scale mapping, and long-range delivery (Ackerman and Strickland, 2018). This platform is generally considered more robust to extreme environmental conditions due to higher airspeed capabilities, a trait which has been verified in several field campaigns (Elston et al., 2011; Frew et al., 2020). However, as fixed-wing sUAS must maintain significant airspeed to avoid stall, they require larger takeoff/landing footprints and have relatively limited maneuverability compared to rotorcraft. These characteristics make the platform more challenging to rapidly deploy and less suitable for tasks such as infrastructure inspection,

[1]https://www.ecfr.gov/current/title-14/chapter-I/subchapter-F/part-107

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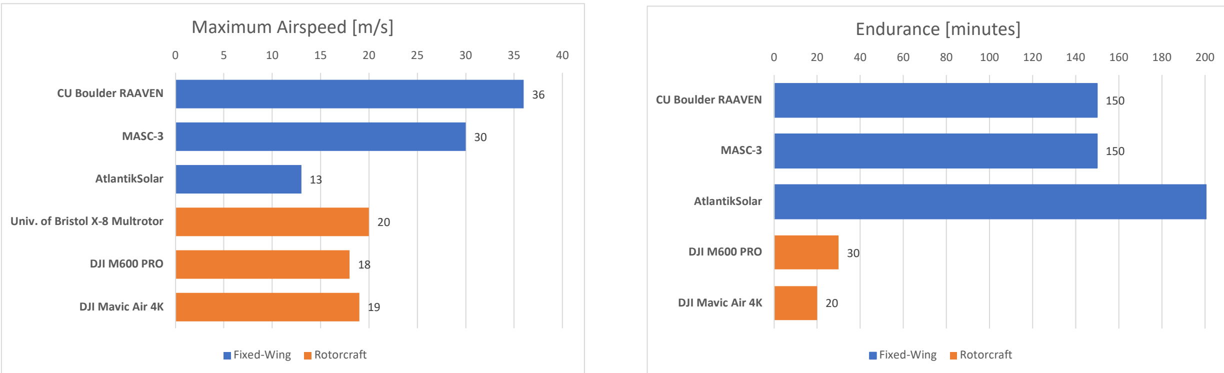

(a) Available maximum airspeed specifications.

(b) Available endurance specifications. Atlantiksolar has demonstrated endurance of 4860 minutes.

Figure 1. Available performance specifications of the aircraft platforms surveyed in this work. Fixed-wing aircraft generally exhibit greater endurance and airspeed than rotorcraft.

where cameras need to be carefully positioned relative to a stationary target. Furthermore, fixed-wing aircraft generally require additional pilot training, which can add to operational costs. However, robust autopilot and autonomy algorithms are making fixed-wing sUAS easier to control and pilot.

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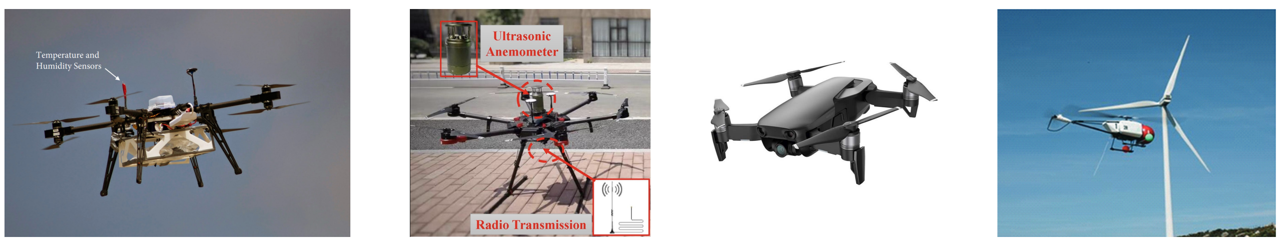
Platform	Type	Endurance	Payload Mass	Cruise Speed	Max. Speed	Use Case	Commercial Availability
CU Boulder RAAVEN	Fixed-Wing	150 min	<1 kg	17 m/s	36 m/s	Offshore ABL Sampling	Derived from Ritewing Drak (∼$5000)
MASC-3	Fixed-Wing	150 min	1 kg	19 m/s	30 m/s	Turbine Wake Measurement	Derived from NAN Xplorer 3 (∼$2000)
Atlantik Solar	Fixed-Wing	81 hours	0.9 kg	8.6 m/s	13 m/s	Persistent Flight, Inspection	Custom
Univ. of Bristol X-8 Multrotor	Multirotor	—	<0.5 kg	N/A	20 m/s	Atmospheric measurement	Custom
DJI M600 Pro	Multirotor	30 min	1 kg	N/A	18 m/s	Turbine Wake Measurement	Available (∼$6000)
DJI Mavic Air 4K	Multirotor	20 min	N/A	N/A	19 m/s	Visual Wind Turbine Inspection	Available (∼$800)
SAHARA Helicopter	Helicopter	—	∼1.3kg	N/A	—	Infrared Blade Inspection	Custom

Table 1. Performance characteristics of the sUAS platforms surveyed in this work. Dashes or N/A indicates information is unavailable or not applicable, respectively.

(a) CU Boulder RAAVEN (b) MASC-3 (c) Atlantiksolar

Figure 2. The fixed-wing sUAS platforms surveyed.



(a) Univ. of Bristol X-8 Multirotor (b) DJI M600 Pro (c) DJI Mavic Air (d) SAHARA Helicoper

Figure 3. The rotorcraft sUAS platforms surveyed.

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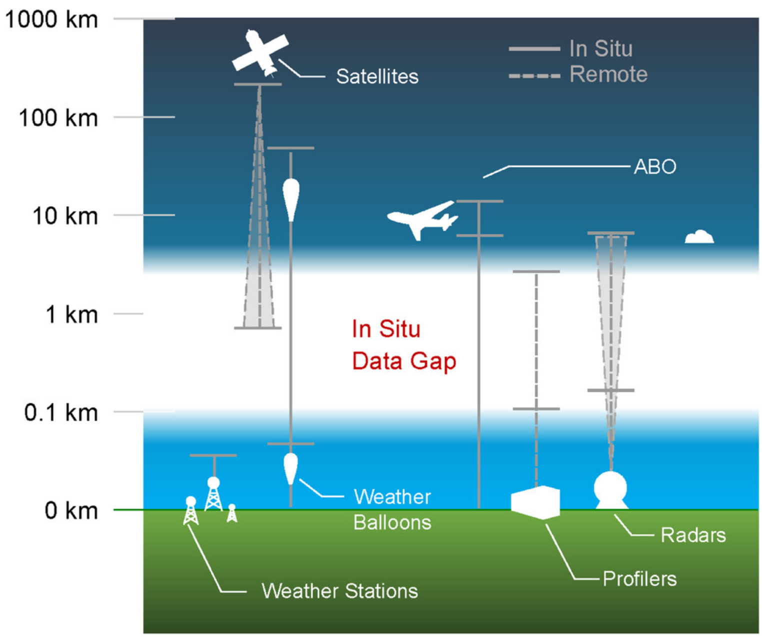

Figure 4. The in situ observation gap in the atmospheric boundary layer (Pinto et al., 2021).

95 ## 2.2 Common Atmospheric Measurements with sUAS

sUAS are commonly used to take in-situ atmospheric state measurements, and have become increasingly popular for targeted information gathering missions in the atmospheric boundary layer (ABL). These are regions of the atmosphere where standard measurement platforms such as meteorological towers are expensive, sparse, and/or cannot reach (Pinto et al., 2021). Across the world, offshore meteorological towers have been deployed to take in situ measurements at altitudes ranging from 27m to 97m (Bodini et al., 2019; Ohsawa et al., 2007; Kim et al., 2019). While remote sensing techniques can provide some information, the complete thermodynamic state must be inferred. This region (100m - 1km AGL) of sparse in situ measurement is known as the “observation gap" (Figure 4) and sUAS have strong potential to help fill this void (Pinto et al., 2021).

Wind vectors are a standard sUAS measurement, often estimated by default in modern open-source autopilots (Meier et al., 2015). Two-dimensional horizontal and three-dimensional winds can be estimated via a variety of methods. Two-dimensional winds can be inferred from airspeed and inertial velocity data through kinematic relationships (Cho et al., 2011; Lawrence and Balsley, 2013), or through filters tightly coupled with aircraft state estimation (Tian et al., 2021). Rotorcraft can produce horizontal wind estimates by measuring state offsets during hover, then backing out wind vectors using a model of the aircraft dynamics and drag (Wetz et al., 2021; González-Rocha et al., 2023). While this approach eliminates the need for external sensors, hover state must be maintained to take wind measurements (Abichandani et al., 2020). Furthermore, turbulence measurements are limited with this technique due to flow distortion (Wetz and Wildmann, 2022).

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Figure 5. A frame from an onboard video caputured aboard the Super RAAVEN sUAS, showing convective storm formation in the U.S. Great Plains.

For three-dimensional wind estimates, several techniques and sensor suites can be deployed. Perhaps most commonly used are multi-hole probes, which provide pressure measurements at prescribed locations on the probe head to determine the wind vector in the aircraft body frame (airspeed, angle of attack, sideslip angle). Combined with high-fidelity attitude and inertial velocity measurements, one can calculate the corresponding inertial wind vector (Tian et al., 2021; Elston et al., 2015; Lenschow and Spyers-Duran, 1989). Other, less common methods include flush air sensing (Laurence and Argrow, 2018), pressure strips (Laurence et al., 2016), alpha-beta vanes (Tian et al., 2018), and sonic anemometers (Thielicke et al., 2021).

Recently, lidar has also been deployed for horizontal wind measurements (Kellner et al., 2019; Mendez et al., 2022; Vasiljević et al., 2020). Cameras are also commonly mounted to sUAS (Figure 5), which can be used to conduct relative bulk wind estimation (Nichols, 2017).

Wind measurements are commonly augmented with in-situ air pressure, temperature, and humidity measurements that can be readily made via small, lightweight, power efficient sensors such as the Vaisala RSS904 (Barbieri et al., 2019).

Direct atmospheric measurements from sUAS can also be used to infer other atmospheric features, such as turbulence characteristics. For instance, turbulence dissipation rate (ϵ) and temperature turbulence structure function parameter (C_T^2) can be estimated via post-processing spectral analysis of pitot probe and cold-wire anemometer probe data, respectively (Lawrence and Balsley, 2013). Measurements such as these can be costly to acquire in offshore environments, but have large implications in offshore wind modeling and forecasting (Bodini et al., 2019).

2.3 Swarming

A fundamental challenge of using sUAS for operational atmospheric measurement is the limited endurance and airspeed. The result is reduced operational conditions and limited range, which has a significant impact on use cases. As land-based operations of sUAS are logistically easier, the ability of sUAS to conduct missions within offshore wind farms from the coast should be considered. A 2020 global survey of offshore wind farms indicated 87.5% are less than 30km from shore (Díaz and

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Soares, 2020). This distance is easily covered by modern fixed-wing sUAS platforms, which have operational ranges up to 200km. Conversely, rotorcraft are largely infeasible for land-based operations, except for those offshore wind farms within a few kilometers from shore.

To address the limited endurance and range of sUAS within the context of persistent observation, swarming concepts have been introduced in literature. The fundamental concept of swarming is to leverage a team of robotic vehicles to collaboratively conduct a task. The team of robots may be heterogeneous to exploit relative strengths of different platforms, or to enable capabilities that any one robot would be unable to perform. This concept has been demonstrated at length in applications utilizing sUAS such as underground search and rescue (Tranzatto et al., 2022) and communication-aware information gathering (Moon, 2021).

Persistent, distributed environmental monitoring with sUAS necessitates a form of swarming due to limited energy onboard. One concept, referred to as the “3D Mesonet" (Chilson et al., 2019) utilizes a dispersed network of multirotor sUAS to conduct periodic profiles of the atmosphere to collect high-frequency atmospheric state data. These data inform modelling of complex processes within the atmospheric boundary layer, with the goal of ultimately improving the fitness of numerical weather models. The 3D Mesonet is designed to operate autonomously, with minimal human supervision, enabling scalability of the system. The system revolves around a central base station, which contains sensing, decision-making, and docking infrastructure. While a similar base station could be built offshore, the cost and complexity would be significantly greater than the current land-based 3D mesonet concept.

Swarming can also be used to take high spatial and temporal resolution of airflows around wind turbines, as was done by the SWUF-3D multirotor swarm (Wetz and Wildmann, 2023). Through deliberate flight planning, the swarm was able to measure inflow, outflow, and resolve horizontal wake structures. Small atmospheric features such as wind gusts can be resolved at finer resolutions than traditional methods such as long-range radar (Wetz et al., 2021).

Other robotic swarming research directly targets offshore wind farm maintenance with multirotor sUAS (Nordin et al., 2022; Jiang et al., 2023). As multirotors are often infeasible for land-based operations, they are paired with an uncrewed surface vehicle (USV), which provides a platform for refueling.

2.4 Operations

Weather plays a significant role in safe sUAS operations. Due to their small size, weight, and airspeed, sUAS are particularly susceptible to adverse weather conditions. Large unexpected wind gusts can blow the aircraft off course, potentially causing collisions with nearby structures. Strong turbulence and precipitation can reduce aerodynamic performance of the aircraft, ultimately reducing endurance. Local, high-resolution weather models may be used to inform operational decisions before aircraft are deployed (Glasheen et al., 2019). Offshore sUAS operations reduce the severity of aircraft failure, due to the lack of other low-altitude aircraft, people and structures. Quantification and management of sUAS weather hazards will be critical to safely conducting any commercial operation (Roseman and Argrow, 2020).

Other hazards that can affect sUAS operation include GPS failure, communication dropouts, airspace deconfliction, and hardware failures. While ideally avoided altogether, sUAS operators must prepare contingency protocols should a hazard arise.

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To help scale these protocols, autonomous onboard contingency management systems have been developed and demonstrated for high-density, urban, beyond visual line-of-sight (BVLOS) flight (Baculi and Ippolito, 2019). Similar systems can be readily extended to sUAS used in offshore wind operations.

In order to operate lawfully, sUAS operators must obtain proper permissions from aviation authorities. The types of authorization requests that must be submitted are dependant on both the sUAS mission and the country in which operations will be conducted. For offshore wind missions, BVLOS flight approval may be a common mission requirement, in cases where aircraft are operated from shore. Table 2 summarizes BVLOS requirements by region.

Region	Regulating Agency	BVLOS Requirements
United States	Federal Aviation Administration	Requires exemption, waiver completed on FAADroneZone [2]
United Kingdom	Civilian Aviation Authority	Requires either demonstrated technical capability for automated Detect and Avoid (DAA) or airspace segregation [3]
European Union	European Union Aviation Safety Agency	Requires Predefined Risk Assesment (PDRA) and operational authorization from local aviation authority [4]
China	Civil Aviation Administration of China	UAS operation is regulated, permission must be granted by CAAC to fly BVLOS [5]

Table 2. Beyond visual line of sight rules for the United States, United Kingdom, European Union and China.

3 Applications for sUAS for Offshore Wind Energy

We survey potential sUAS applications to support offshore wind energy projects in three areas: wind resource assessment; operational observation; and inspection. Our survey is structured as a series of case studies, where we focus on academic works which deploy sUAS in real-world experiments.

Wind resource assessments are essential studies conducted during the planning phases of any wind farm, both offshore and onshore. In order to understand potential wind energy production it is imperative to fully characterize local winds. This is critical because small deviations of wind speed can cause large reductions in power output (Murthy and Rahi, 2017). Typical wind resource assessments are conducted over the course of one to two years (Brower, 2012). They rely on measurements from many sources including lidar, meteorological (MET) towers, satellites, as well as estimates from numerical weather prediction (NWP) models (Brower, 2012; Probst and Cárdenas, 2010). sUAS have the potential to augment these studies by providing additional in situ measurements in locations.

Continued study of local winds is still necessary even after wind farms are constructed and operational. Operational monitoring provides measurements to evaluate both wind farm efficiency as well as impacts of turbine-flow interactions downstream

[2] https://faadronezone-access.faa.gov/
[3] https://publicapps.caa.co.uk/docs/33/CAP722_Edition_9.1%20(1).pdf
[4] https://www.easa.europa.eu/en/domains/civil-drones-rpas/specific-category-civil-drones/predefined-risk-assessment-pdra
[5] https://droneregulations.info/China/CN.html

of turbines. These studies often rely on the use of lidar, radiosondes, and MET towers (Sun et al., 2020; Bodini et al., 2017). sUAS can provide additional in situ measurements in and around operational wind farms at targeted locations and times.

sUAS equipped with cameras and other tools can conduct surveys to assist wind farm inspections. Operating on their own, sUAS have the potential to inspect faster and more frequently than conventional methods (Liu et al., 2021; Rakha and Gorodetsky, 2018). Offshore locations are a difficult environment in which to conduct traditional crewed operations. sUAS have potential to mitigate natural challenges related to accessing and inspecting offshore wind turbines.

3.1 Augmenting Offshore Wind Resource Assessment

The first potential application of sUAS relates to the planning phase for offshore wind farms. Wind resource assessment requires wind measurements on-site for about two years (Brower, 2012). More measurements produce a fuller picture of available wind resources. sUAS are capable of providing in situ wind and atmospheric state measurements at targeted location to augment observational records. There are several cases of atmospheric research conducted in offshore locations using sUAS which demonstrate potential for offshore wind resource assessment.

3.1.1 Case Study I: ATOMIC (Fixed-Wing)

In January and February 2020, the CU Boulder RAAVEN sUAS was deployed as part of the Atlantic Tradewind Ocean–Atmosphere Mesoscale Interaction Campaign (ATOMIC). The objective of this campaign was to collect atmospheric data with the aim of improving understanding of trade-wind cumulus clouds (de Boer et al., 2022). The RAAVEN completed 39 flights each lasting about two hours. The launch point was located on the north east coast of Barbados, and measurements were taken up to 2 km off the coast of the island (Figure 6). The RAAVEN was equipped with a *miniFlux* payload instrument suite co-developed by the National Oceanic and Atmospheric Administration (NOAA) and Cooperative Institute for Research in Environmental Sciences (CIRES). The *miniFlux* suite contains a Vaisala RSS421 pressure temperature humidity (PTH) sensor, a Black Swift Technologies multi-hole probe, a custom fine wire array, and a VectorNav VN-300 inertial navigation system (INS). The RAAVEN logged about 80 hours of flight time between January 24 and February 15. It is believed that the RAAVEN flight capabilities allowed for high quality observations spanning length scales from 5 cm to 130 km with data acquisition rate of 10 Hz. As a quality control, RAAVEN data was compared to radiosonde observations. These comparisons showed good agreement, validating the platform and sensor suite (de Boer et al., 2022).

This study demonstrates the RAAVEN's ability to be flow over the ocean for extended periods of time. The objectives of ATOMIC dictated the flight paths, which limited flights further offshore. Given the flight duration and cruising speed it is reasonable to conclude that it is within the RAAVEN's abilities to fly and take measurements 5 to 10 kilometers off the coast, which are the approximate distances of the Block Island Wind Farm (Ten Brink and Dalton, 2018) and the planned Cape Wind project respectively (Phadke, 2010).

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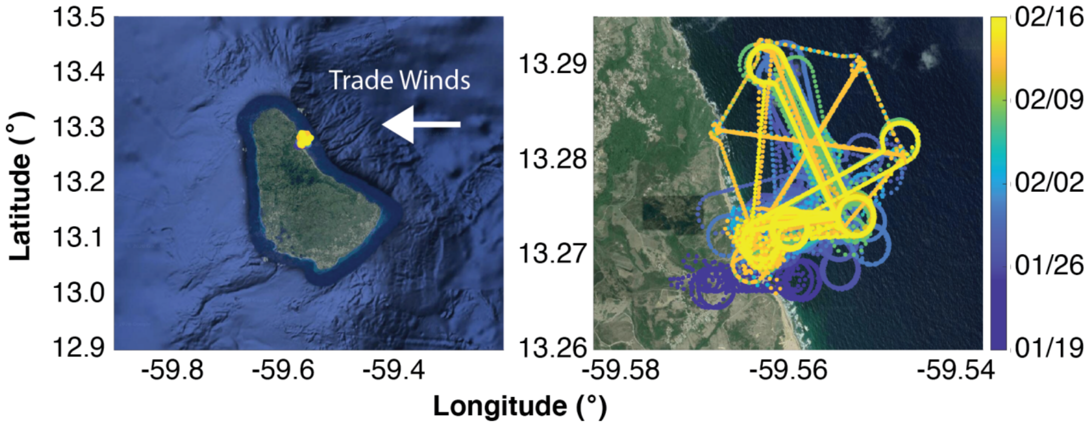

Figure 6. Flight Path of the RAAVEN for missions off the east coast of Barbados between January and February 2020 (de Boer et al., 2022).

3.1.2 Case Study II: Atmospheric Sampling on Ascension Island (Multirotor)

Two flight campaigns were conducted on Ascension Island between 2014 and 2015 by researchers from the University of Bristol. The goal of this campaign was to demonstrate the capability of multirotor sUAS to take temperature and humidity profiles in an coastal environment while flying beyond visual line of sight (BVLOS) (Greatwood et al., 2017). A custom-designed octocopter sUAS was deployed. The payload included a GE fast-tip FP07 thermistor temperature sensor as well as a IST P-14 Rapid capacitance humidity sensor.

Typical flights lasted around 20 minutes which allowed for one 2.5 km vertical profile per flight (Figure 7). Climb rates were approximately 5 m/s. The sUAS encountered winds of about 8 m/s. Data from radiosondes were used to validate the multirotor measurements.

This experiment demonstrates the capability of sUAS multirotors to make accurate measurements during BVLOS flights in a coastal environment. While 20 minutes of endurance is not long enough for many land-based flights, it would be sufficient if deployed from existing marine platforms or naval vessels.

3.2 Operational Observation

The second potential application of sUAS relates to the observation of operational offshore wind farms. Continued atmospheric measurement around installed turbines is required for performance evaluation of a wind farm, while providing helpful information that can be used to improve future wind farm projects. sUAS are capable of taking targeted measurements in and around wind farms to augment operational observations. There are several cases of wind farm studies which rely on sUAS to collect wind and turbulence data.

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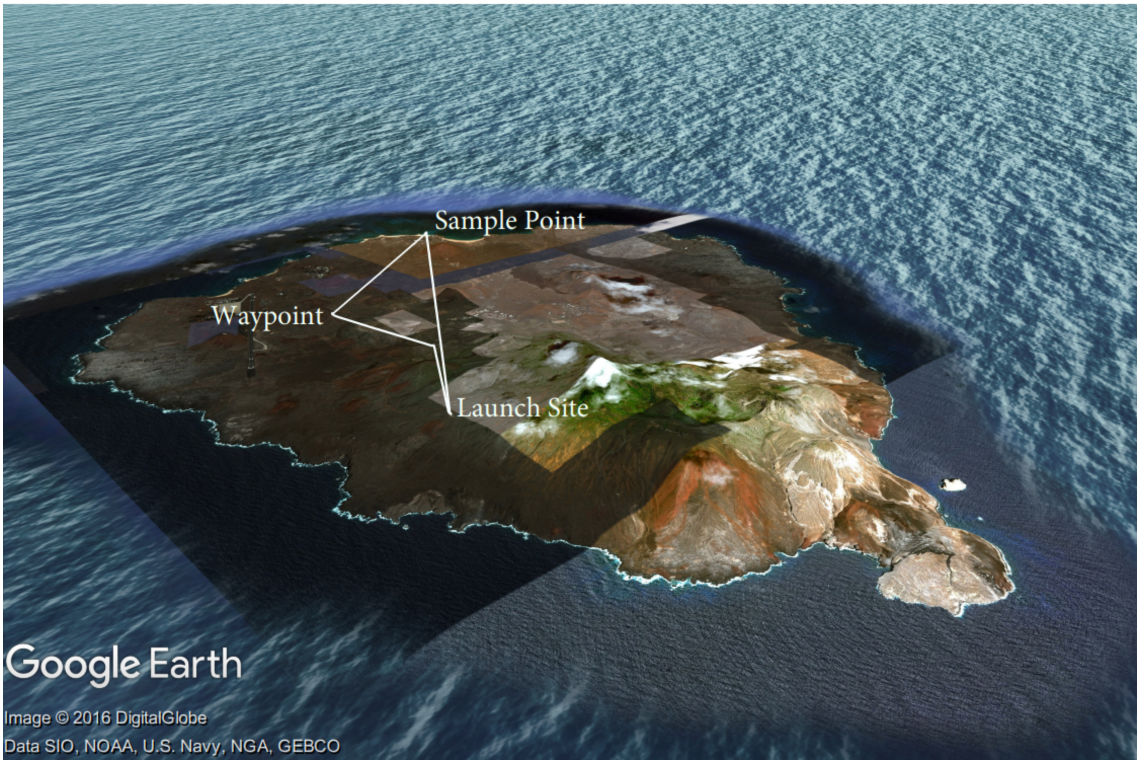

Figure 7. sUAS flight plan on Ascension Island for campaigns between September 2014 and July 2015 (Greatwood et al., 2017).

3.2.1 Case Study I: Wind and Turbulence in Wind Turbine Wakes (Fixed-Wing)

A group from the University of Tübingen studied the downstream wind behind operating turbines in 2019 at the Jade Wind Park on the coast in northwest Germany (Mauz et al., 2019). For the study, a MASC fixed-wing research sUAS was deployed.

The MASC made a single 15 minute flight to collect data downstream of a turbine. Over the course of the flight, the average wind speed was about 8.8 m/s, with average turbulence kinetic energy (TKE) of about 0.1 m^2/s^2. Data from the flight showed strong velocity deficits in the region immediately down wind of the turbine (Figure 8). The sUAS also detected tip vortices at the edge of the wake (Rautenberg et al., 2019). This study provides an example of how sUAS are being used to aid wind farm operational observation. Given the capabilities of the MASC and the coastal location of the flight, it would be feasible for a similar sUAS to take the same measurements at an offshore wind turbine site.

3.2.2 Case Study II: Detecting Wind Turbine Wakes with sUAS (Multirotor)

In 2022 researchers from Hunan University, the Chinese Academy of Sciences, Weifang University and the Royal Melbourne Institute of Technology published results for a study on the use of multirotor sUAS for detecting wind turbine wakes (Li et al., 2022). For this work a DJI M600PRO hexacoptor sUAS was deployed. The sUAS was equipped with a 0.5 kg SA210 ultrasonic

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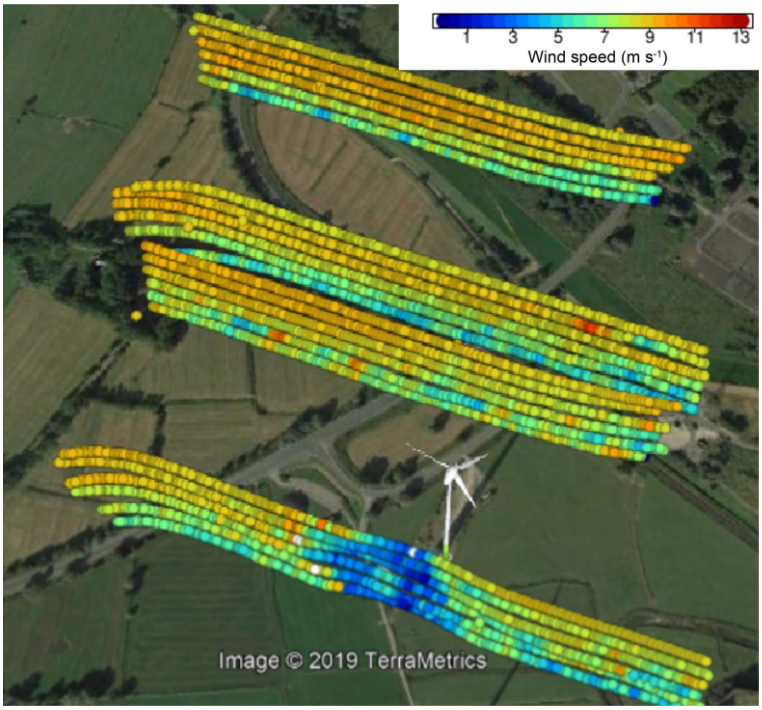

Figure 8. MASC Turbine Wake detection: velocity deficit (Mauz et al., 2019).

anemometer capable of sensing winds at speeds ranging from 0 to 50 m/s. The ultrasonic anemometer samples at a rate of 1 Hz and is accurate to within 0.5 m/s for winds less than 10 m/s, and within ± 5% for wind speeds between 10 and 50 m/s. The reported wind direction is accurate to within 4°. The sUAS was equipped with radio communication to transmit real-time anemometer data to the ground station.

The sUAS was flown at a coastal wind farm site located in Eastern China, where 20 2MW turbines are installed in a single row (Figure 9). The turbines have a hub height of 70 meters and blade length of 40 m. Flights lasted 30 minutes, during which the sUAS completed vertical profiles of wind speed and turbulence intensity.

To simultaneously detect inflow and outflow features, two aircraft were deployed in two different formations. Via the first formation, the two sUAS studied inflow (Figure 10a). One sUAS hovered at hub height, while the second completed a vertical profile from 10m to 120m. In the second configuration, the two sUAS studied both inflow and outflow (Figure 10b). One sUAS hovered upwind of the turbine at hub height while the second sUAS completed vertical profiles downstream of the turbine. Flights were conducted in close proximity, within 2-10 rotor diameters of the turbine.

The wind data collected from these flights showed clear wake signals via increased turbulence and velocity deficits downstream. In-situ wake data allows for evaluation of wake model fitness. This demonstrates the ability of teams of multirotor sUAS to take precise, coordinated measurements around installed turbines.

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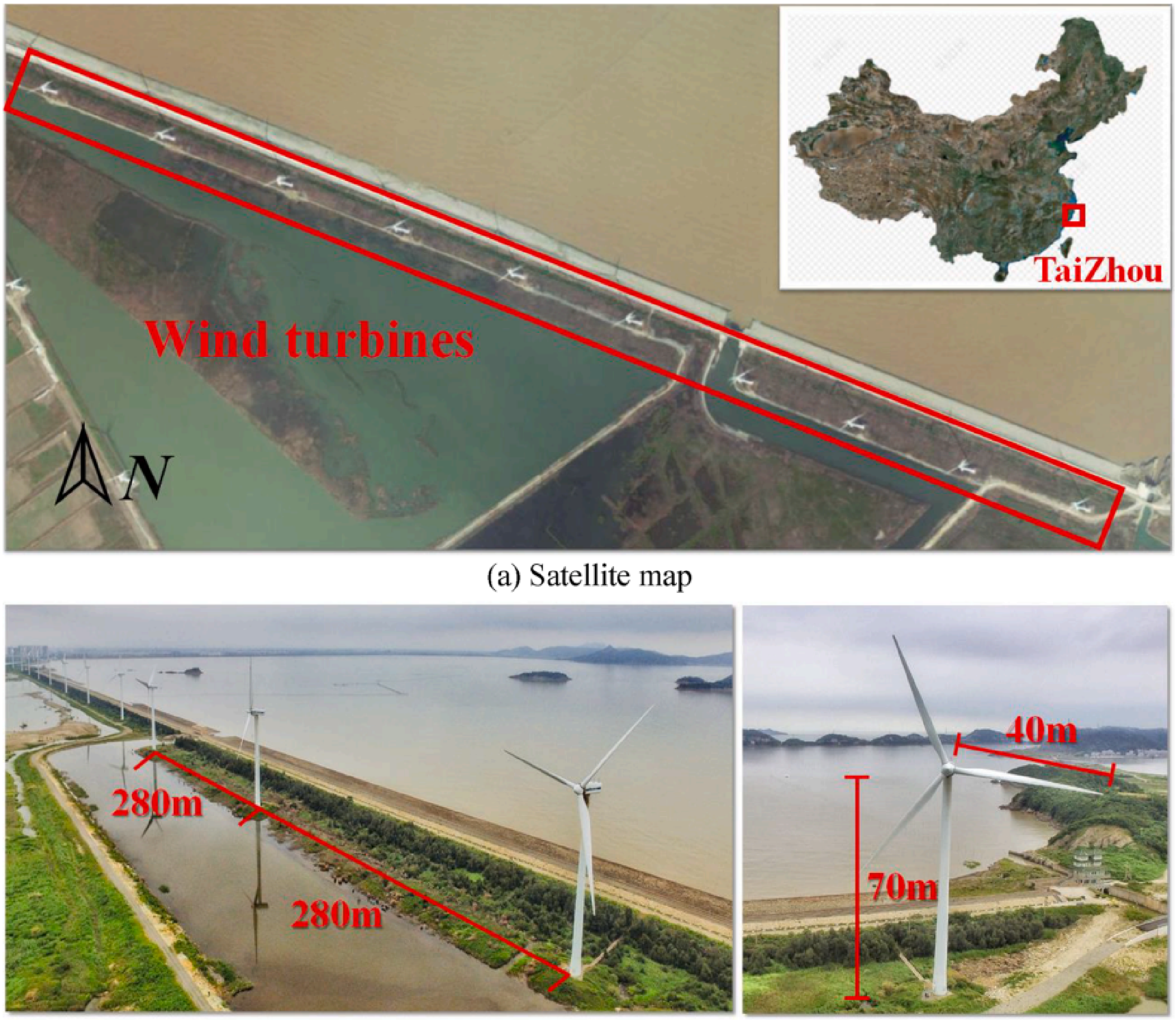

Figure 9. Wind farm site located in Eastern China (Li et al., 2022).

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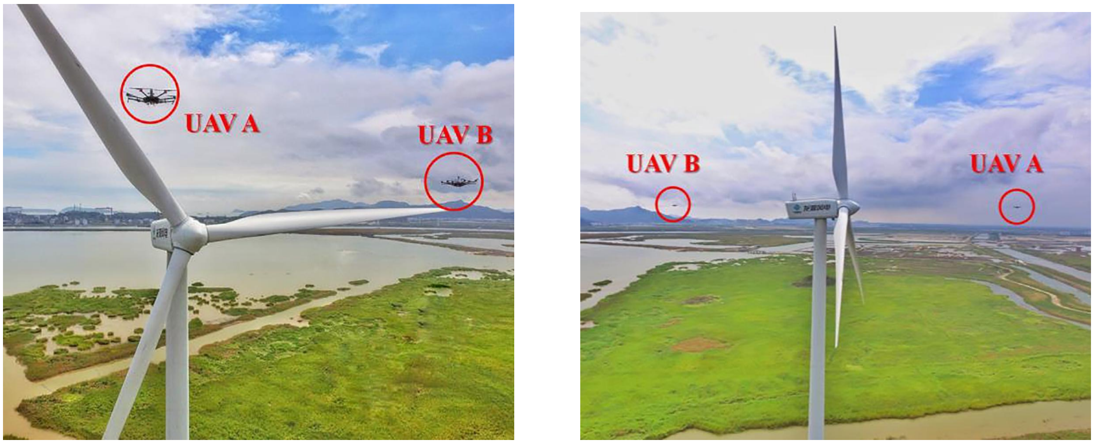
Wind Energy Science Discussions



(a) Flight Formation A (b) Flight Formation B

Figure 10. DJI M600PRO sUAS flight configurations around a wind turbine (Li et al., 2022)

3.3 Support for Wind Farm Inspections

The third potential application of sUAS is inspection of offshore wind farms. Recently, sUAS have been established as a tool used for maintenance inspections for buildings and other structures (Liu et al., 2021; Rakha and Gorodetsky, 2018). One of the primary payloads used for inspection are cameras. Today, small cameras have the ability to take high resolution photos and video which can be used to identify visible damage. Several studies have been conducted which demonstrate the ability of sUAS to effectively inspect wind turbine structures.

3.3.1 Case Study I: General Inspection (Fixed-Wing)

The Autonomous Systems Lab at Eidgenössische Technische Hochschule Zürich has conducted several research studies related to structural inspection via sUAS (Bircher et al., 2015; Oettershagen et al., 2015). In a 2015 project, they demonstrated the ability of fixed-wing sUAS to be used for inspection operations. For the study, the AtlantikSolar sUAS was deployed to conduct an aerial inspection of a campus. The sUAS carried a FLIR Tau 2 long-wavelength infrared camera and an Aptina MT9V034 camera which has the ability to communicate with a ground station in real-time.

At the time of Oettershagen et al.'s publication in 2015, The AtlantikSolar had completed more 49 flights of flight time spanning over 85 hours total. The aircraft was able to successfully complete a campus inspection of a campus providing clear images and footage (Figure 11). The AtlantikSolar is a prototype research sUAS, however it's flight log demonstrates the ability of fixed-wing sUAS to conduct surveys that require high endurance.

3.3.2 Case Study II: Blade Icing (Multirotor)

Researchers from Iowa State University published results from a project studying icing on wind turbine blades (Gao and Hu, 2021). A DJI Mavic sUAS equipped with a high resolution camera photographed iced turbine blades.

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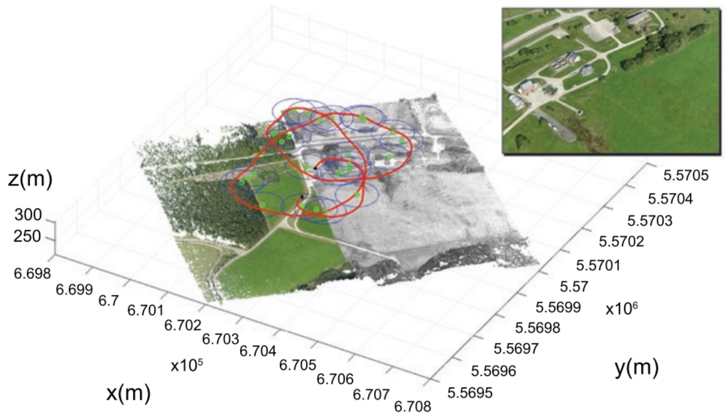

Figure 11. AtlantikSolar sUAS inspection path at Eidgenössische Technische Hochschule Zürich campus (Oettershagen et al., 2015).

The DJI Mavic Air 4K is a commercially available off-the-shelf multirotor sUAS which is currently priced around \$800. Takeoff mass is less than 1 kg, max accent speeds is 8 m/s, and max flight speed at sea level is 19 m/s. With no wind, the maximum flight time is 40 minutes providing a range of 30 km.

For this study, flights were completed in 2019 over a period of 4 days at a wind farm located near the East China Sea. The wind farm has 31 turbines installed, each with power rating of 1.5 MW. The turbines were constructed in 2016 along mountain ridges about 1500 m above sea level, with hub heights of 78 m and rotor diameters of 100 m. The Mavic surveyed the turbine blades, 50 m in length, and photographed iced regions (Figure 12a). The images were analysed and showed ice thicknesses up to 300 mm at the tip (Figure 12b).

This project provides a concrete demonstration of an inexpensive, commercially available sUAS being used to inspect operational wind turbines. Icing is a relevant issue, particularly for offshore wind farms located in northern areas like the Baltic and North Seas which are at moderate to high risk for icing events (Figure 13)(Ribeiro et al., 2021).

3.3.3 Case Study III: Blade Cracks (Helicopter)

In 2015 researchers from the Center for Advanced Aerospace Technologies in Seville, Spain published a study on identifying cracks on wind turbine blades (Galleguillos et al., 2015). For this work a rotorcraft sUAS equipped with a FLIR P620 infrared camera was deployed. The sUAS was an electric helicopter developed by for research purposes. Two flights were conducted each lasting 18 minutes with speeds limited to 1 m/s . The first flight on a turbine with 10 meter long blades at a site in Tarifa, Spain, and second, on a turbine with 40 meter long blades at a site in Granada, Spain. The sUAS was kept a minimum distance of 5 meters from the blades of the first turbine, and a minimum of 10 meters from the second turbine (Figure 14). The turbines were stationary during inspection. After processing the images, thermal patterns caused by a pitch break system as well as

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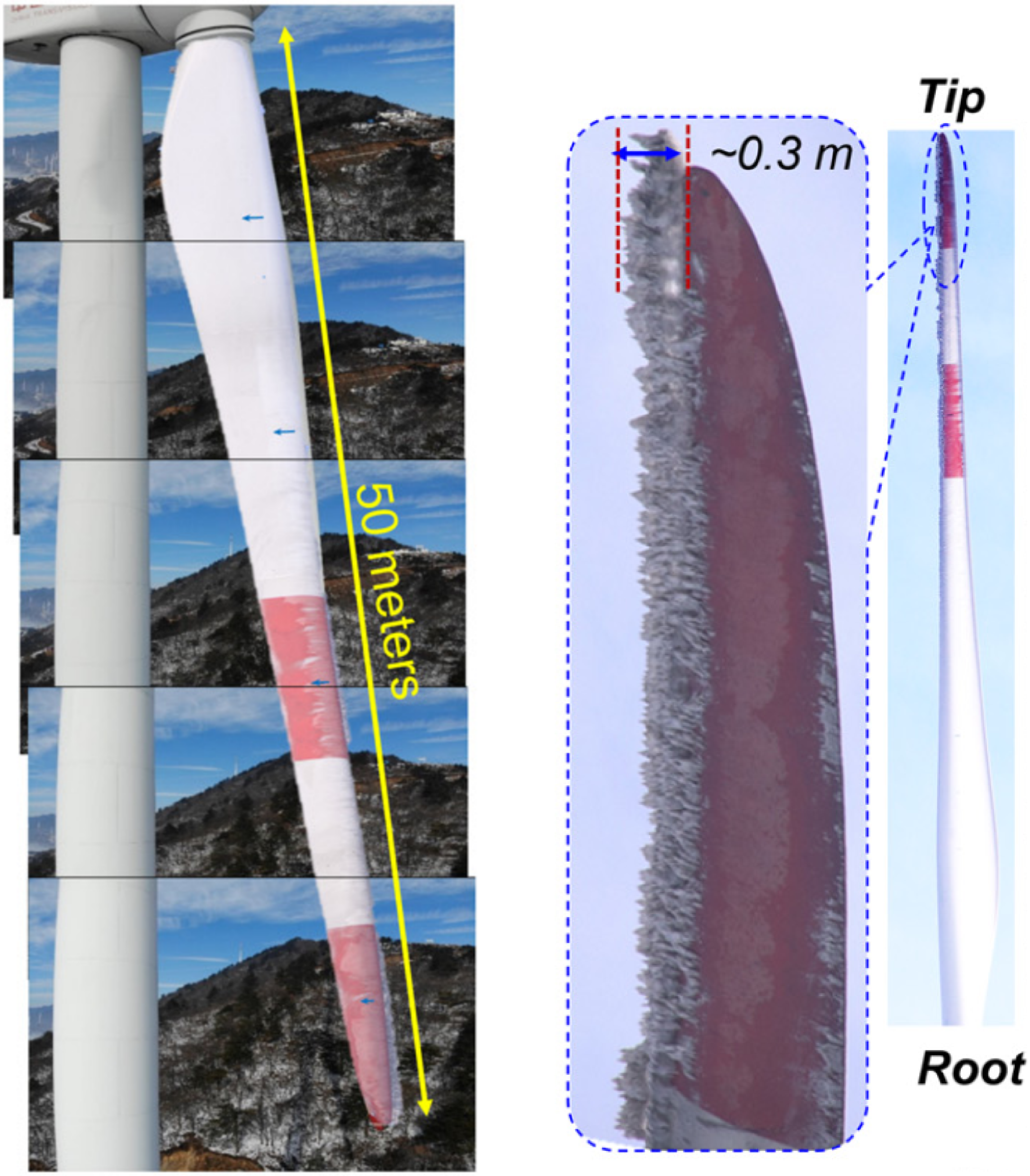

(a) Flight Formation A

(b) Flight Formation B

Figure 12. Stitched (a) and blade tip (b) photos from a DJI Mavic Air depicting turbine icing at a site near the South China Sea (Gao and Hu, 2021).

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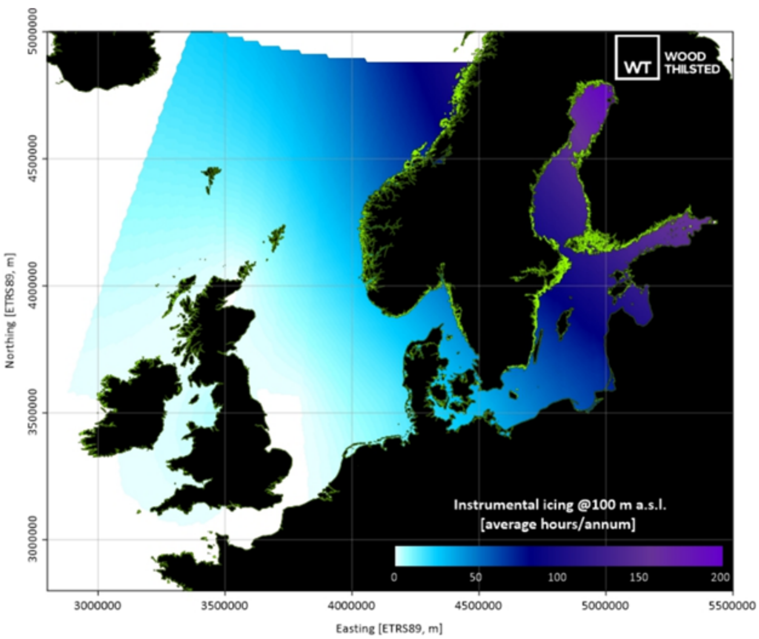

Figure 13. Map of instrumental icing, in hours per year, at 100 m above sea level (Ribeiro et al., 2021).

Figure 14. Path Planning for sUAS around a turbine blade.

from bonding areas between shell and beam were visible from the data for both flights. The thermal patterns are caused by temperature variations of 0-5°C and are indicative of cracks.

This work demonstrates that sUAS can and have been used to identify structural deficiencies in installed wind turbines. This type of technique can similarly be used for offshore sites to aid inspection and maintenance efforts.

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4 Conclusion

This survey presents the capabilities and applications of fielded sUAS as related to offshore wind farms. Generally, fixed-wing sUAS are likely a strong candidate for long duration, long range missions, such as persistent observation or operations from shore. Rotorcraft are more agile, and a strong candidate for close-up operations such as inspection. However their limited range and endurance necessitates a platform at sea from which to operate. Both aircraft types have been shown to be suitable platforms for in situ atmospheric state sensing, a critical task for modeling atmosphere-turbine interaction and wind resource assessment.

This survey has shown sUAS capabilities in various application settings, however studies deploying sUAS in and around offshore wind farms are lacking. Challenges specifically related to offshore operations (i.e. communications, corrosion, weather) remain open for study, and need to be investigated via field deployments. Advanced swarming algorithms and demonstrations will help increase spatial-temporal resolution of measurements for both fixed-wing and rotorcraft platforms. Advanced autonomy algorithms will be key to leveraging operator time and reducing overall mission costs. While coordination between autonomous rotorcraft and surface vessels has been proposed (Jiang et al., 2023), validation of such complex operations remains to be seen. Overall, we believe application of sUAS to offshore wind farm development, monitoring, and maintenance may ultimately help to reduce project cost while improving outcomes.

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Competing interests. The authors declare no competing interests.

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