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ORIGINAL PAPER

Advances on the integration of transport drones into offshore wind farms

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Abstract

The rising demand for renewable energy production capabilities following Europe's green energy revolution is expected to lead to a large expansion of offshore wind farms (OWF) into the exclusive economic zones of North and Baltic Sea. Automated cargo drone delivery of maintenance and repair materials could significantly lower the high costs of wind farm maintenance. For efficient and safe operations, drones must be properly integrated into the maritime domain and the OWF. The Upcoming Drone Windfarms (UDW) project between the German Aerospace Center (DLR) and the energy provider Energie Baden-Württemberg (EnBW) targets several aspects of these central challenges. This paper presents the main concept for a fictitious drone transport mission to OWF Hohe See, operated by EnBW in the North Sea, which acts as reference scenario to develop the integration and operation concept as there is no model drone transport service available today. The presented work focuses on the interaction between the drone and the wind farm's infrastructure as this is expected to be one key element to benefit from the automation potential of drone usage. For the interaction, appropriate concepts for communication were developed, implemented, and eventually demonstrated in a simulated transport mission in an onshore wind farm. The paper contributes to this topic with the identification of necessary infrastructure extensions to enable a reliable communication, the interaction between the drone and the wind farm, and a summary of shared information. Also, the technical setup of the flight tests and main findings are presented.

Keywords Offshore · Transport · Drone · Communication

Abbreviations

ADS-B	Automatic dependent surveillance broadcast
AIS	Automatic identification system
API	Application programming interface
BVLOS	Beyond visual line of sight
EASA	European aviation safety agency
EEZ	Exclusive economic zone
GCS	Ground control station
GUI	Graphical user interface
ICAO	International civil aviation organization
KTAS	Knots true airspeed
LoRA WAN	Long-range wide area network
MQTT	Message queuing telemetry transport
PRM	Probabilistic roadmap method
OSS	Offshore sub-station
OWP	Offshore Wind Park
TLS	Transport layer security
UDW	Upcoming Drones windfarm
VLOS	Visual line of sight

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VPN	Virtual private network
WTG	Wind turbine generator

1 Introduction

The project Upcoming Drones Windfarm (UDW) funded by the 7th Energy Research Program of the Federal Ministry for Economic Affairs and Climate Action (BMWK) is a research collaboration between the German Aerospace Center (DLR) and the energy provider Energie Baden-Württemberg (EnBW) together with associated partners active in the field of offshore wind farm (OWF) design, logistics, and certification. Especially, the maintenance part heavily relies on specialized ships and helicopters and thus provides a fascinating use-case for drones. These could be used for transporting spare parts, tool sets, and maintenance material from the mainland to an OWF in the North and Baltic Seas. To perform this task, the integration of the drone into the wind farm and the maritime environment must be considered and technological gaps must be identified. This requires further upgrades of the drone on the one hand and extensions to the wind farm and other maritime infrastructure important for the mission on the other hand to ensure the safe and efficient operation of the drone. The research presented in this paper focuses on the communication concept between the drone and to be identified stakeholders of the drone mission, for example, the drone pilot, the OWF, or points of contact to the maintenance process. The communication is also necessary to inform the autonomously operating drone of relevant factors impacting the mission, so it can adapt the mission or synchronize with the mission frame set by the maintenance process. Such mission adaptations include changes to the planned transport route. The planning of the transport route is influenced by many environmental factors of which wind and weather, operational state of the wind farm, traffic information, and time window in which the cargo must be delivered, are currently accounted for. The implementation of the communication requires to define a reliable software and hardware communication network for drone and OWF and to define frequency and content of the data to be exchanged between drone and stakeholders.

A first version of the mission concept presented in this paper has been formally published in [1], where the planning and preparatory work for an onshore flight test to evaluate the concept was presented. The flight test was conducted in October 2023. Test results and derived findings for the concept are presented in this paper.

In the past, several efforts were made to evaluate currently available drone products and integration concepts with emphasis on the applicability for inspection of wind turbine generators (WTGs) and delivery of cargo to OWFs. In general, the delivery process requires vertical-take-off and landing (VTOL) capabilities to adapt to the spatial limitations of wind turbines. Examples for these types of operations are the efforts of energy providers Vattenfall in [2], Energy Denmark in [3], Equinor in [4] and of logistics company DSV in [5]. Similar intention can be found in the research project ADD2WIND in [6] with a focus on delivery of spare parts to the wind turbine generators (WTG). However, all mentioned sources refer to implementations of line-of-sight (VLOS) supervised drone delivery for either short flights as a sky crane in [2] or beyond-line-of-sight (BVLOS) delivery as in [3] and [4]. Regular BVLOS operations for cargo delivery in harsh environments have been implemented by the Norwegian Research Centre (NORCE) to deliver research stations in Antarctica using a fixed-wing drone without VTOL capability, but with a cargo capacity of up to 100 kg. [7] To the knowledge of the authors, no regular drone transport system for OWFs, especially for BVLOS operation, has ever been implemented. To still be able to derive meaningful requirements for the communication, a model of a plausible drone transportation mission and according embedment into a maintenance process has to be designed first.

This paper contributes to this issue by providing a fictitious transport mission from the mainland to an OWF operated by EnBW, which was based on operational documents [8–10], and [11] on maintenance procedures as well as procedures of manned helicopter transport missions and according infrastructure. These documents are provided by EnBW and give concrete insight which allows to identify stakeholders as well as their possible interfaces or interactions to the drone which define concrete requirements for the communication. As other OWF operators are similar to EnBW regarding procedures and infrastructure, it can be assumed that the identified stakeholders and interactions can be generalized in this context.

The OWF *Hohe See* located within the *German Bight* was chosen to be the target of the transportation mission as it is fully operational and thus provides concrete boundary conditions. This approach is complemented by a brief survey of other environmental factors, such as sea traffic and the organization of offshore air traffic. The defined transport mission and interfaces to stakeholders allow to elaborate hardware and software concepts for the communication with the drone as well as a definition of data to be exchanged. The developed communication concept has been successfully evaluated regarding its feasibility in an onshore flight test, in which the exchange of data and interaction of the drone with an onshore wind farm was implemented using public cellphone networks and modifications to the wind farm to exchange data with the drone.

The paper is structured as follows. Section 2 details the overall scenario of the transport mission and introduces the target OWF *Hohe See*. After the introduction of *Hohe See*, Sect. 3 provides a review of EnBW's documents on *Hohe See's* maintenance processes and offshore operation as well as a brief analysis of environmental factors impacting the transport mission. Section 4 presents the simplification of the complex maintenance operation and provides an overview of stakeholders relevant for the mission with special emphasis on their responsibilities, capabilities, and interfaces. Details on the designed mission are provided in Sect. 5. Also, first steps to implement a realistic wind situation and a timely delivery window as mission boundaries into an automatic planning algorithm are presented. Section 6 highlights the conceptual interaction of the drone with the OWF and other stakeholders and provides solutions how to implement a communication network between drone and OWF. The exemplary implementation of the communication concept into a flight experiment and results of the experiment are presented in Sect. 7. The paper concludes with Sect. 8, which summarizes the main findings and gives an outlook on ongoing work.

2 Scenario for concept case study

The wind farm *Hohe See* is operated by EnBW and is located in the North Sea about 95 km north of the German island of *Borkum*. *Hohe See* consist of 71 wind turbines of type Siemens SWT-7.0-154, each having a rotor diameter of 154 m and a nacelle height of 105 m.

The wind farm provides the target for a fictitious drone transport mission to deliver replacement parts to one of the wind turbines within the farm. The transport mission has interfaces to the maintenance process which is responsible for the coordination of work force within the wind farm. Additionally, it defines the conditions of the mission, such as scheduling of a time frame and characteristics of the delivered cargo. The mission incorporates the pick-up of cargo on the mainland, the flight to the wind farm, navigation around and within the wind farm, the landing on a landing pad mounted on the nacelle of a target wind turbine, and the return flight back to the mainland.

An essential aspect for this operation is to make operating conditions and environmental conditions of the wind farm available to the drone to enable safe and efficient motion planning. Wind turbines are naturally equipped with wind measuring sensors and control systems, which provide basic weather information and information about each wind turbine's operating state.

3 Environmental considerations

3.1 General operations and infrastructure for aircraft in the North Sea

With the construction of offshore platforms for oil production or research purposes and the emergence of OWFs in the North Sea, a transport network has developed in recent decades to supply the offshore outposts with personnel, components, and other goods. Transport vessels and helicopters are the primary means of transport, and are used by wind farm and platform operators depending on the type of goods to be transported and the time factors involved. Over time, regulatory constraints have arisen for helicopter flights, which are aimed at increasing the safety of offshore flights. In addition, infrastructures and operational procedures have been established that can serve as models for unmanned cargo transport with drones. The operating procedures are defined in operating manuals, which specify regulatory requirements of the aviation authorities and safety-motivated requirements of wind farm operators being responsible as employers of the deployed personnel. These requirements also serve as boundary conditions for the service providers of offshore helicopter flights. In the following, some relevant aspects of the existing rules for offshore helicopter flights are presented, as a future implementation of drone delivery may follow its example. However, as drone delivery will share the same airspace with the offshore helicopters, the drone must adapt to the present offshore traffic. A waypoint network defining fixed transport routes have been established for helicopters which are for example published on the *helidecks.de* website [12]. Figure 1 gives an overview of the helicopter waypoint network with predefined flight routes. These flight routes are used to specify and publish flight plans, which make it easier for other traffic participants and air traffic control to avoid collisions. In addition, in the event of an air accident, rescue services can find their way to the scene of the accident more quickly and in a more targeted manner. EnBW requires helicopter crews to prepare a flight plan with a flight route based on the waypoint network and the planned flight times, as well as the continuous updating and activation of the plan using the *helidecks.de* website [9].

The network consists of waypoints defined to control the air traffic of the adjacent airports on the mainland and waypoints that define routes to avoid restricted airspaces which are shown in Fig. 2 as well as to navigate around existing or planned wind farms, platforms, or other operational areas. Waypoints located within restricted airspaces may only be used if the airspaces are not active or special clearance has been given.

The waypoint network is of special interest for drone transport missions, as it already defines time efficient routes within open corridors between existing and planned OWFs or other areas while ensuring sufficient reachability of all these areas. Therefore, an adoption of these advantages for the planning of drone flight paths by adapting to the waypoint network seems reasonable. However, sharing the same transport routes with manned offshore traffic creates the necessity to enforce collision avoidance by separating the traffic as far as possible and creating awareness of each

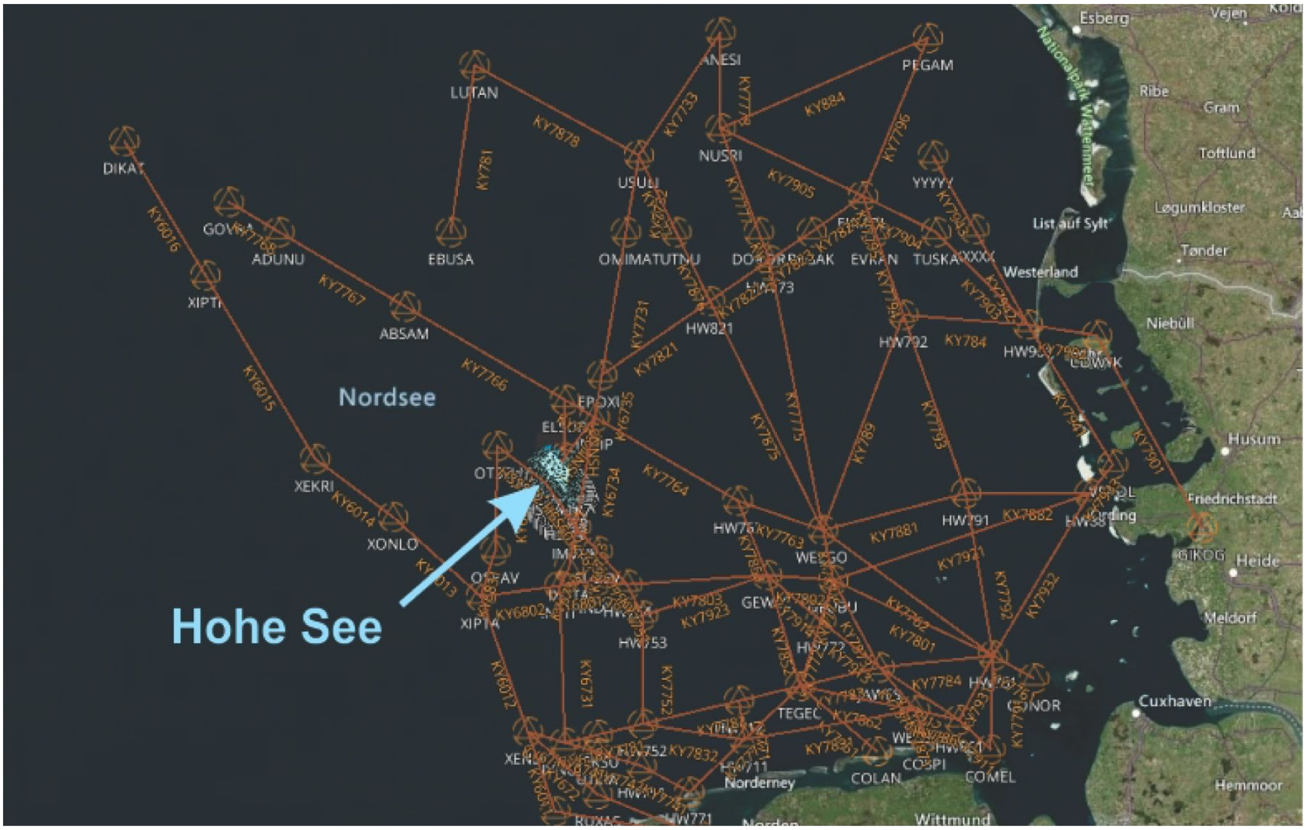


Fig. 1 Waypoint framework used for helicopter transport missions over the *German Bight*

other. The following boundary conditions for the execution of manned offshore flights create options to implement separation and awareness:

- Minimum altitude: 150 m above the highest obstacle at a distance of 150 m on all sides, 300 m at night.
- Transits through OWFs may only be performed with sufficient distance to wind turbines, the minimum distance is 900 m
- Main cloud base: min. 600 ft (~ 200 m) during the day and min. 1200 ft (~ 400 m) at night
- Flight visibility: 1.5 km during the day and 5 km at night, during the day the flight visibility may drop to 800 m for a short time if land visibility is available
- Wind: max. wind speed (mean or gust) generally up to 50 kts (~ 100 km/h), wind operation areas in OWFs have their own wind limitations up to which an approach is possible
- Weather: no flights during thunderstorm or icing conditions.

In addition, there are numerous requirements for the training of flight personnel and passengers, as well as the equipment of the helicopter used. It is worth mentioning here that helicopters must be equipped with an Automatic Dependent Surveillance-Broadcast system (ADS-B) to increase situational awareness and avoid collisions.

Based on these requirements, possible ways to enforce collision avoidance and awareness between drones and manned traffic would be to limit drone flight below the minimum altitude of manned flight and to make ADS-B systems mandatory for drones as well.

3.2 Traffic infrastructure-ADS-B and AIS

ADS-B is a transponder system used primarily by air traffic to broadcast current motion data and metadata such as aircraft type and route of an aircraft at predefined intervals. The motion data mainly contain the position of the aircraft in global coordinates (e.g., WGS 84), the altitude above a reference surface, and the course and airspeed over ground. Air traffic control, but also other traffic participants, can receive the data provided by radio (usually transmitted omnidirectionally) and thus obtain a more precise picture of the situation of air traffic in an airspace than would be possible, for example, using an airborne radar. ADS-B helps traffic participants prevent collisions, as the proprietary ADS-B system can receive

Fig. 2 Restricted airspaces above the *German Bight* reaching to sea level

signals from other aircraft in the vicinity, informing the crew of the presence and intentions of air traffic. ADS-B has been mandatory in the EU since Dec. 7, 2020, for large aircraft with a take-off weight of 5.7 metric tons or more or a cruise speed of more than 250 KTAS (knots true airspeed) in cruise flight [13]. In addition, the equipment is mandatory in certain special cases, such as commercial offshore flights. Since ADS-B devices and antennas are relatively compact, they can be placed on board drones without much effort, making them visible to other traffic participants. To do so, however, it is mandatory that other traffic participants have their own ADS-B device. Research in [14] suggests that future drones might be equipped with additional surveillance technology to increase the chance of detection and awareness of other aircraft. However, compatibility of these systems with established systems like ADS-B or other maritime identification systems needs to be evaluated.

In addition to the airborne activities, there is a lot of vessel traffic in the North Sea. Figure 3 shows a heat map of all recorded ship routes in 2022 and a snapshot of ship traffic on August 30, 2023 using [15]. Tracking of ships is made possible by AIS, whose radio data are received from various stations and fed into the Internet. The figure shows that a planned transport route from the mainland to *Hohe See* crosses several highly frequented routes of maritime traffic leading parallel to the coast line or between the wind farms. Especially, the harbors of *Hamburg* and *Bremerhaven* draw a lot of maritime traffic traveling through the *German Bight* to reach the Atlantic Sea.

To avoid manned air traffic, a height separation to its minimum altitude if 150 m above sea level is mandatory and flights in or below 120 m as mandatory over the German mainland might be a reasonable choice. However, large cargo ships approaching major sea ports like *Hamburg* reach heights of about 70 m, like the *HMM Algeciras*, which

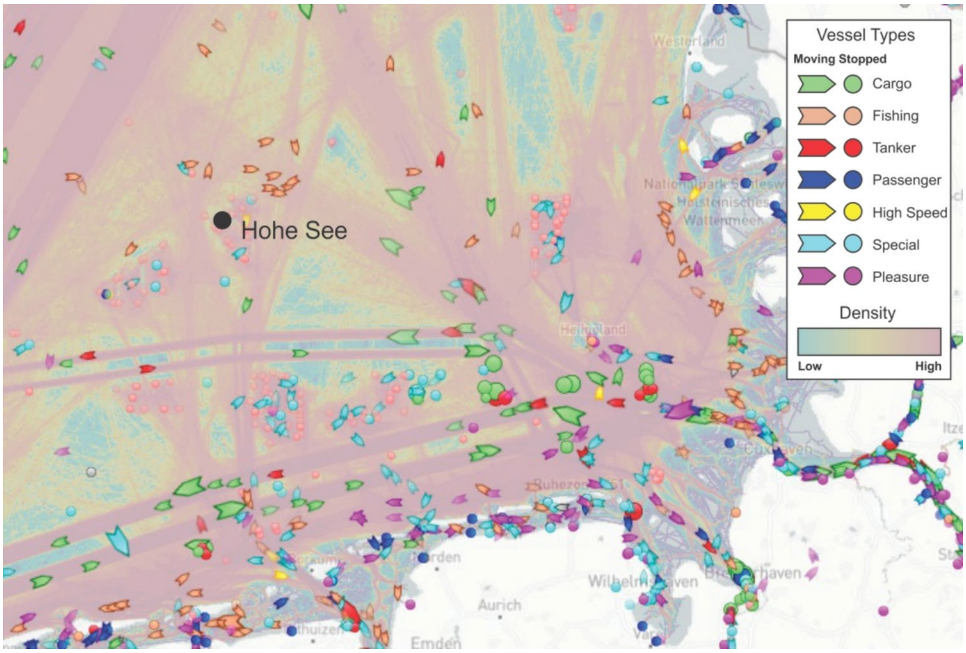


Fig. 3 Ship movements in the *German Bight* tracked using AIS at midday of 30.08.2023 (highlighted) and traffic density map of 2022 (background)

already visited the *Hamburg* harbor [16]. Thus, collision avoidance with large vessels has to be considered and may be based on available AIS data.

The AIS system for shipping broadly follows the same basic idea of the ADS-B system. Vessels equipped with AIS continuously transmit their current position, course, speed, and meta information about the vessel, such as call sign, type, cargo, nationality, et cetera. The transmission intervals depend on the ship class and speed and vary between 2 s and 3 min. AIS is obligatory for ships on international voyages with a gross tonnage (GT) of 300 or more and for national ships with a GT of 500 or more [17]. There are exceptions, e.g., for historic ships. The mentioned GT corresponds to cargo ships from approx. 30 m length, while motor boats and even larger yachts for recreational purposes are not subject to the AIS obligation. Therefore, it should be mentioned that AIS can only cover a part of the maritime traffic, but definitely the most relevant large vessels. In and near wind farms in the North Sea, only commercial ships are allowed. Since they are mandatory equipment with AIS, a good recognition of the ships in the OWF can be assumed. ADS-B and AIS are technically slightly different systems despite the fact that they are used for the same purpose. There is no coupling or crossover between them and none is planned for the foreseeable future. An exception to this is a class of AIS transceivers used in search and rescue aircraft. AIS technology could be used for the drone to avoid overflying vessels on route to or within the OWF. However, the system is currently not technically able to make air traffic visible to sea traffic users and, to the authors notice, there is no intention to do so. Therefore, the drone cannot notify the vessels of its presence using AIS.

3.3 Infrastructure in offshore wind farms for helicopter transports

EnBW's OWFs in the North Sea are specially equipped for helicopter transport. Each wind turbine carries a so-called heli-hoist area on its nacelle, which allows the lowering of people or goods from helicopter with the help of a winch. The requirements for a hoist area in German OWFs is defined in [18] and a simplified visualization of the procedure is given in Fig. 4. The requirements in this document give detailed information on the approach procedure which can be adapted for the drone mission.

For reasons of statics and the limited space available, it is not possible to land on the wind turbine with the helicopter. For the hoist maneuver, the WTG is put into a special hoist stop by the OWF control room. This causes the rotor to slow down until it comes to a stop in a certain position. Preferably, the nacelle of the turbine in question is turned 90° clockwise to the wind, so that the hoist area is blown sideways by the wind. The rotor blades are then moved, so that the leading edge of the blade facing the wind is parallel to the horizon (so-called L + position, see Fig. 5). Alternatively, the rotor can be stopped in the Y position, in which one rotor blade is facing downward. The rotor and nacelle positions are selected to reduce interference of the helicopter with the wind turbulence field created by the rotors during its approach. For this reason, approaches with drones will likely be conducted in the same way.

Once the OWF is ready for the hoist maneuver, it indicates its status to the control room via its data terminal and to the helicopter crew by issuing a permanently green light on the hoist platform. For a drone to recognize the

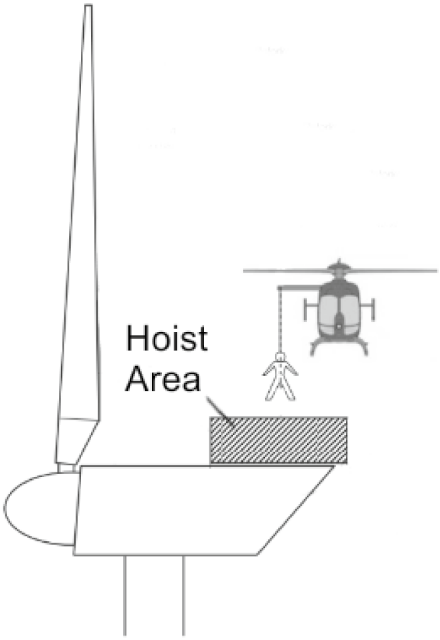


Fig. 4 Helicopter during hoist maneuver

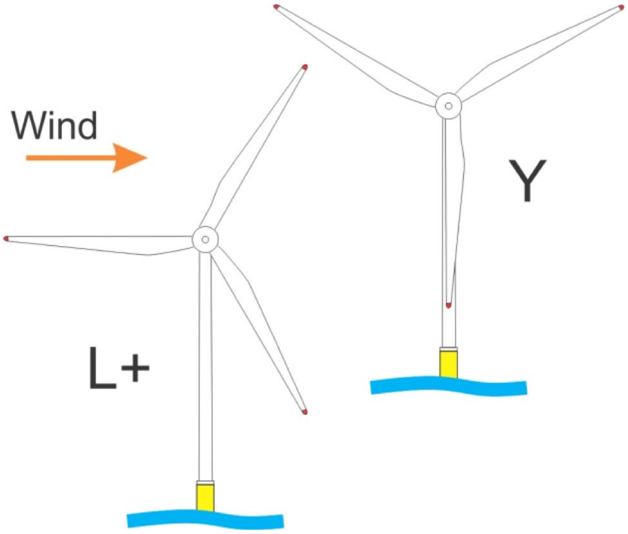


Fig. 5 Hoist positions of WTG blades

hoist-ready status, the green light indicator needs to be digitalized and transmitted.

In addition to the wind turbines, there is also an offshore sub-station (OSS) at the *Hohe See* wind farm, which is equipped with a helipad. Generally, OSS usually have a hoist area, but not always a helipad. Furthermore, weather measuring instruments relevant for aviation are located on the OSS, which, in addition to wind measurements, also record precipitation, visibility, and cloud base and provide them to the helicopter pilot via an automatic radio announcement. It should be noted that future wind farms will increasingly not have an own OSS, as the wind turbines prefer to feed directly into the transmission system operator's grid to save costs.

3.4 Weather conditions

The maritime weather might be the most challenging environment on earth to operate drones due to the prevailing high winds, humid and salty air, and wide spread temperature range. When it comes to approach, landing, or hoisting of cargo at the WTG nacelle, precise control of the drone in the gusty wind condition must be assured. Figure 6 shows a boxplot of the recorded wind speeds at WTG nacelle height for a WTG of OWF *Hohe See* for each month of the year 2024. The used dataset was provided by EnBW and extracted from the OWF data system. The dataset contains 10-min-mean wind measurements every 10 min for the whole year, except 3 days in August when the WTG was out of operation.

The orange bar marks the mean wind speed, the box indicates the first and third quartiles of the data, and the bars indicate the measured minimum and maximum wind speed. As to be expected, the wind values tend to lower values in the spring to summer time and to higher values in fall and winter season. Lower winds and higher temperatures are more pleasant and safe conditions for maintenance personnel and the lower wind also causes lower loss of revenue during the downtime. Thus, the majority of maintenance operation is taking place in the months from April to September. Within this time frame, the highest third quartile of data is about 14 m/s of mean wind in April, meaning that 75% of wind measurements are at this value or lower. To put this value into perspective: current operational limitations of use-case relevant cargo drones like the GRIFF 60 or the Airbus VSR700 lie at maximum wind speeds of 20 m/s [19, 20]. This wind tolerance level results in a good availability of the drone during the maintenance season and can be used as a requirement for design and development of other drone systems intended for this use-case.

4 Involved roles

From the drone's point of view, several people with corresponding tasks and functions must be involved to ensure an efficient and safe flight. The tasks and functions of the persons are usually clearly defined in operating manuals and process documents. However, for this concept, the involved roles are on a higher level than those defined in flight operation manuals and boundary conditions are not known in detail, so roles must be defined on a more generic level. In the following, the drone and the roles required for drone flight are first described with their approximate tasks and authorities, and then, their interaction with each other and

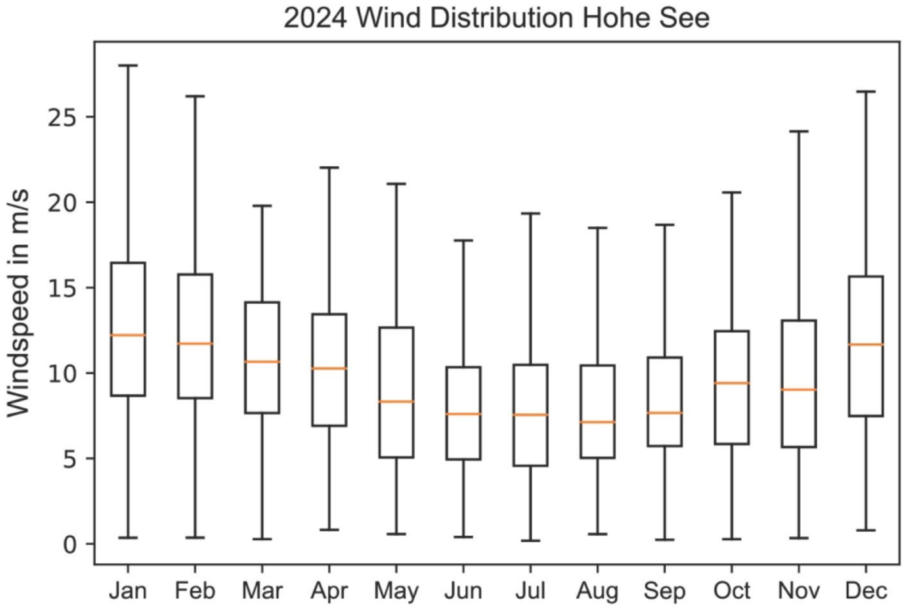


Fig. 6 Box plot of recorded wind speeds in 2024 at nacelle height in OWF Hohe See

with the drone is resolved. Figure 7 gives an overview of the interaction between the drone and OWF as technical assets and the roles, which are filled out by humans. The information related to the OWF operator is colored blue, while actions of the drone provider are in green color. Automatically issued information of drone is in black color. Defined data exchange between drone and OWF is highlighted in orange. Figure 7 and the following description of roles focus on the essential interactions for a nominal drone mission. The figure also implies relations to other roles, like the rule-making authorities responsible for the drone mission frame, rescue services to cover distress situations, and other traffic sharing airspace or sea area.

4.1 OWF

Each WTG and the OSS within the OWF are connected to a server framework via sea cable and publish all available status data in frequent intervals of a few seconds. The control room subscribes to all publishing OWF assets and is able to control the operational state of each WTG.

The OSS and several WTGs carry AIS transponders, which make the OWF visible to sea traffic, but also collect data on vessels present in the near vicinity of the OWF and within the OWF. These data can be made available to the drone for the planning of paths leading around the vessels.

4.2 Drone

It is assumed that the deployed drone is designed for the particular transport mission and maritime use. This means that the drone can safely stow and transport the payload and is not affected by environmental conditions at sea (rain, high humidity, and salty air). The drone has a high level of automation compared to the current state of the art, meaning that it is capable of performing both standard maneuvers such as take-off and landing, as well as waypoint navigation autonomously, and can respond to anticipatable problems in exceptional circumstances. These include avoiding other air traffic and emergency procedures, such as rescheduling and landing at alternative landing sites or, in extreme cases, intentionally terminating the flight by an emergency ditching/landing or planned crash of the drone. The drone's high level of automation allows a mission to continue even in the event of a sporadic loss of communication with the ground station or drone pilot. In the event of prolonged interruptions or total loss of communication, tested fail-safe mechanisms are in place that either guarantee a safe condition for the drone (e.g., by returning to the launch site, landing on alternative targets, and flying holding patterns) or sacrifice the drone by aborting the flight (intentional crash) in favor of human or infrastructure safety. For the safe execution of the mission, the drone is equipped with appropriate equipment. Equipment requirements generally arise from the approval process for the operation of the drone and, if applicable, from the wind farm operator. Proof of compliance with the requirements of the approval process for equipment and functions of the drone can be provided equally by the manufacturer and the operator of the drone (drone provider). In case of doubt, this task is incumbent on the drone provider as the applicant for the permit.

4.3 Drone provider

Similar to today's helicopter air traffic, the operator of wind farms will not act as operator of the transport drones itself,

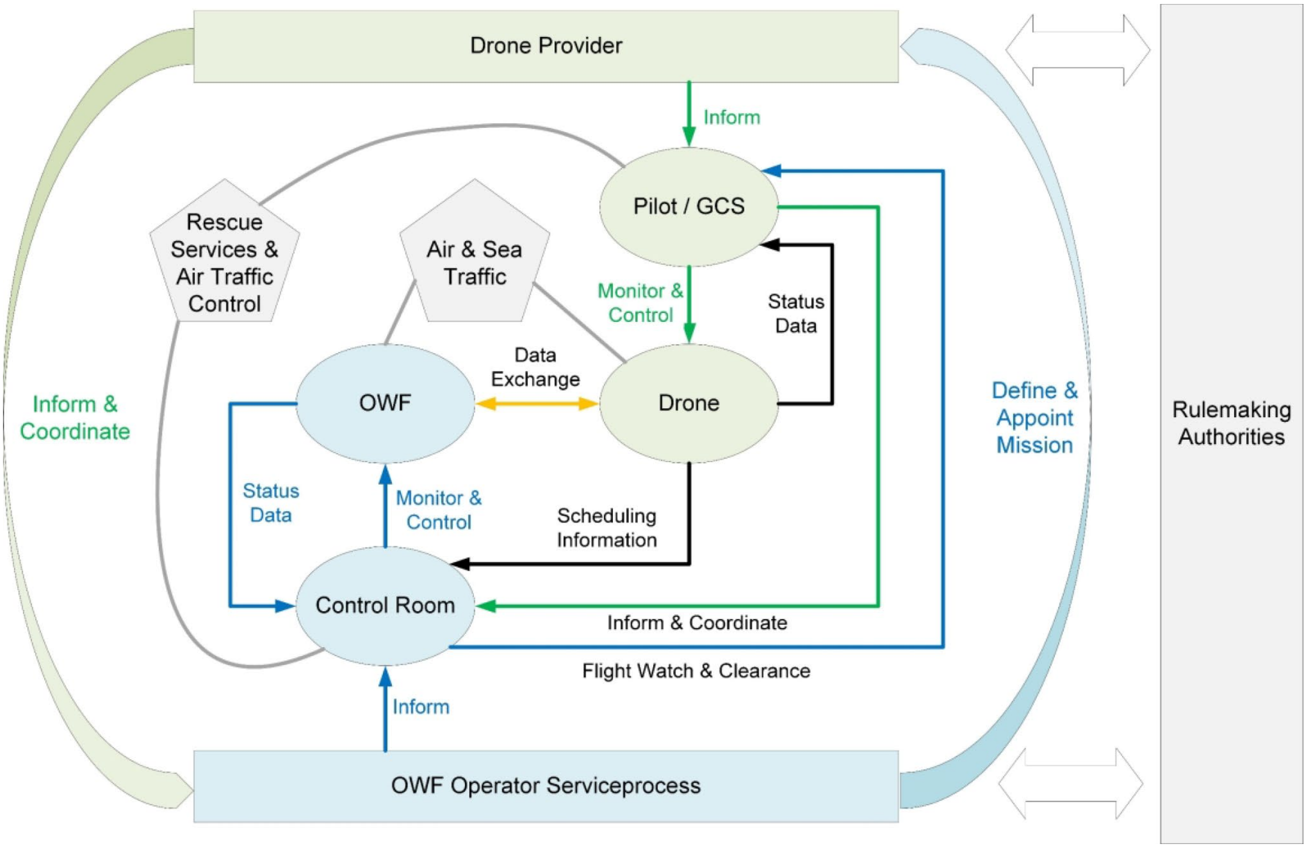


Fig. 7 Flow of information and actions between the defined roles

but will contract a drone provider to carry out transport missions. For transport missions, the drone provider will maintain a fleet of drones and appropriate personnel for maintenance, control (pilots, operators), and loading (fuel, transport goods) of the drones or pass these tasks to subcontractors. The drone provider fulfills the requirements set by EASA and the Federal Republic of Germany for a company that performs commercial drone flights. In simple terms, these requirements generally mean that the drone provider is registered as an operator of drones and ensures that the proper condition of the drones through maintenance or repair measures and organizational requirements (e.g., insurance or quality management) are kept. In addition, the drone provider must ensure that deployed personnel are appropriately trained for the tasks and that their level of training is sufficient for the transport mission.

4.4 Drone pilot

Throughout the duration of the transport mission, the drone will be monitored and controlled by a drone pilot. The drone pilot is in charge of the drone during this time and has the final say in safety-critical decisions. The point of operation is a control center or ground station for drones, which combines status information of the drone and, if necessary, information of the environment (e.g., other air traffic, maritime traffic, etc.) and provides input options for influencing the drone. Since the drone is sufficiently automated, there is no provision for direct intervention in the drone's actuators. Therefore, the ground station is not equipped with input devices, such as joysticks and thrust levers. The drone pilot may be guiding multiple drones simultaneously and can influence the flight of the drone by sending commands at a higher level of execution. The higher execution level includes commands such as changing the flight destination, initiating emergency actions (evasive action, emergency landing, flight termination), or authorizing standard tasks such as take-off and landing, flying in and out of holding patterns, authorizing continued flight, et cetera. The main task of the drone pilot is to be able to manage one or more drones at the same time, i.e., to ensure a smooth mission by communicating with air traffic control, control room, or transport order management. If not otherwise implemented, the pilot acts as the communicator of the drone, asking for example for clearances and instructions for the execution of the mission or supporting the situational awareness of the control room or other traffic participants through messages. A second important task is to ensure the safety of the drone and its surroundings. This includes the early detection of special or even dangerous situations and the initiation of appropriate measures, such as adapting the mission by sending commands to the drone to reschedule the flight. Furthermore, in case of occurrences (collision, crash, ditching, etc.), the pilot is responsible for emergency management. The pilot then has the duty to report the emergency to all involved parties and authorities and to initiate the rescue chain by enforcing the emergency response plan.

4.5 Wind farm control room

The control room is continuously manned and controls and monitors the WTGs and the OSS of one or more wind farms. The control room is informed of all operations affecting the wind farm (presence of vessels, work on turbines, transport flights). Therefore, the control room must be informed by the drone or drone pilot of all activities related to the wind farm, and the control room issues appropriate clearances for entry and landing or take-off and departure from the wind farm. The control room does not have direct control over the drone, but can exert influence through predefined ways of communication with the drone or drone pilot. It is possible for drone status information to be shared with the control room, so there is constant situational awareness of all drone flights. The control room is, however, not expected to interact with the drone mission except giving clearances on a high level, e.g., for entry or approach. Further interaction or control would require knowledge on the UAS and can thus not be expected. The control room is integrated into the rescue chain and as such can act in parallel or in coordination with the drone pilot in the event of an emergency.

4.6 Service process

Depending on the task, a wide variety of processes and organizations are required for the operation and maintenance of OWFs. For reasons of clarity, the individual processes are simplified and combined into a so-called service process. From the perspective of drone operations, the service process defines the mission content and its boundary conditions in advance of the mission and has defined interfaces to influence the mission after its launch. The boundary conditions of the transport missions include, for example, the staging period for the goods to be transported, as well as the delivery period for arrival at the wind farm, which the service process transmits to the drone provider, so that it can prepare the transport mission. Ideally, the transport mission is not time-critical, i.e., the transport can be planned days in advance and the delivery window is also a few days, so drone availability and weather are not critical constraints. In the event that parts need to be transported in a time-critical manner, e.g., because otherwise the wind farm could run into a blackout, the OWF operator's service process staff should have a quick way to order a delivery quickly and efficiently. This could be done using a computerized order process, which is defined between the drone provider and the service process. The service process informs the control room of the necessary details of the upcoming transport mission, so that it can coordinate the OWF and ongoing processes accordingly.

5 Conceptual drone transport mission

In the following, the concept for the unmanned transport mission is explained using an exemplary mission sequence from the drone's point of view. The transport mission begins with the OWF operator's service process requesting a transport mission from the drone provider, specifying the cargo to be transported as well as boundary conditions for the delivery (e.g., the delivery period and destination). The drone provider then ensures that a drone and operating crew suitable for the mission (drone pilot and any personnel for refueling/loading) are available and schedules the flight for the drone by registering it within the service operations portal of the wind farm operator. In addition to drone availability, constraints such as weather can also play a role in scheduling. Analog to the operational process for helicopters, a probable flight path is planned using known boundary conditions and a flight plan is filed. To synchronize the drone's arrival at the OWF with maintenance or other activities, the drone continuously shares its estimated time of arrival with the control room which informs the service process. Before the drone is launched, it is loaded and system checks are performed to ensure that the drone is operating correctly. These checks can be performed by a ground crew or fully automated by the drone itself. Prior to launch, the drone contacts one or more networks to obtain necessary and up-to-date data to perform the flight. This includes the following:

- Updating existing geospatial information (e.g., new obstacles and flight routes).
- Current weather information along the entire flight route and especially at the launch site and the target wind farm.
- Special information such as flight route closures or the establishment of new or temporary restricted flight areas.
- Air traffic information such as planned routes of other offshore flights, to achieve collision avoidance at an early stage (e.g., by scheduling).
- Current operational information at the wind farm, e.g., that the target is likely available and can be approached.

The drone then begins preparing for launch. For the way to the OWF and back, respectively, the transport mission that now follows can be divided into four phases:

- Phase 1: Route planning and take-off, departing in the direction of the transport route.
- Phase 2: Flight along a planned transport route to the wind farm.
- Phase 3: Arrival and flight through the wind farm.
- Phase 4: Approach and landing at the target landing pad.

It can be reasonably assumed that, in regular operations, several destinations may be combined to increase efficiency. For the time being, only the basic mission is considered. Table 1 in the Appendix summarizes the aforementioned mission flow and gives a condensed overview of exchanged messages between mission stakeholders from the point the mission is requested by the service process to the moment the drone leaves the OWF after successful delivery. Drone and drone pilot stay in frequent exchange with the OWF and control room during the mission which already begins before the drone is airborne. However, the following chapters describing the implementation of the drone and OWF communication and the according flight experiment will focus on the data exchange, while the drone is approaching the OWF, which is an important prerequisite for the mission.

5.1 Phase 1

The drone starts planning a flight route based on the received data and shares the planned route with the ground control station. In this process, the drone is able to detect boundary conditions that prevent the execution of the transport mission, such as bad weather in the wind farm, and adjust the time window for the flight. At the end of this planning phase, the mission will be checked by the human operator. This serves to have a human review the automatic planning and to have awareness on the drone pilot himself. It can be assumed that the check will be performed by the pilot. A portfolio of alternative routes including routes for aborting the mission is also planned, so that adjustments to mission like a turnaround, detour, or flight to a safe landing site can be made at any time. The route uses the waypoint network available in the North Sea (see Fig. 1) for path planning and considers altitude buffers to avoid manned air traffic. Since manned air traffic must maintain a minimum altitude of 150 m above ground, the drone's flight path is planned in the altitude band below this altitude, e.g., at 100 m. This height separation between unmanned and manned aircraft is already integrated into the airspace structure in Germany and reduces the risk of collision. Thus, collision avoidance with large vessels has to be considered and may be based on available AIS data. An exemplary route planning from the mainland to the *Hohe See* wind farm is shown in Fig. 8.

The drone pilot checks the planned route and notifies the control room that the drone is ready for take-off. The drone then waits for clearance to take off, which is given as soon as the scheduling of the maintenance process and other factors such as expected traffic or weather conditions meet defined requirements. The drone pilot then initiates the launch of the drone.

5.2 Phase 2

On the flight path, the drone is mostly over the sea and maintains a staggered altitude to stay away from other aircraft. Here, only a relatively narrowband data link is available, which prevents the transmission of larger amounts of data. The drone sends data on position, altitude, airspeed, and essential status information to the ground control station at sporadic intervals (approximately 1 s or more) and shares its estimated time of arrival with the control room. The drone pilot can change the mission at any time by sending a signal to the drone to use pre-planned alternate

Fig. 8 Helicopter waypoint network in yellow color, planned trajectory from the mainland to the OWP Hohe See in blue color

routes, triggering a re-planning of the flight path, or sending a command to trigger a stored function (e.g., return to launch site, emergency flight termination, etc.). Otherwise, the drone follows the planned route until it approaches the target wind farm.

5.3 Phase 3

Before entering the OWF, the drone connects to the broadband radio network and updates all environmental information (wind, visibility, cloud base, etc.). The drone also retrieves the operating conditions of all WTGs located in the OWF to calculate an optimal approach route (shortest route, with as little interaction as possible with wake turbulence from WTGs) through the wind farm to the target landing pad based on this information. Figure 9 shows example routes in the wind farm. These routes could be permanently defined and their selection is based on the current weather and operational situation in the wind farm.

The planned route is shared with the ground station and must be approved before entering the wind farm. The drone obtains permission to enter the wind farm and to approach the target WTG from the control room and initiates the drone's entry. If the approach to the target landing site cannot be made immediately, for instance if the WTG is not prepared for landing, waiting laps are available for the drone, as shown as an example in Fig. 9. In the loitering lap, the drone can circle as energy-efficiently as possible until the flight can be continued.

5.4 Phase 4

Before reaching the target WTG, the drone obtains the exact condition of the target WTG. This includes data indicating that the WTG is shut down (braked) and has assumed a defined state for the approach. If the wind turbine signals to be ready, an approach is performed. From the wind situation, which is obtained at the shortest possible intervals, a final approach path is planned which ensures minimal interaction with the turbulence field of the target or surrounding WTGs. Once planning is complete, a final clearance is requested from the drone pilot. After clearance has been given, the landing is carried out. During landing, the drone continues to retrieve real-time data from the WTG to ensure that conditions for a safe landing continue to match defined limits. For example, if the WTG's rotor brake fails due to a technical defect, it will signal that an approach is no longer possible without danger. The desired behavior of the drone for such complications must be precisely defined at all times during the approach to prevent damage to people and assets.

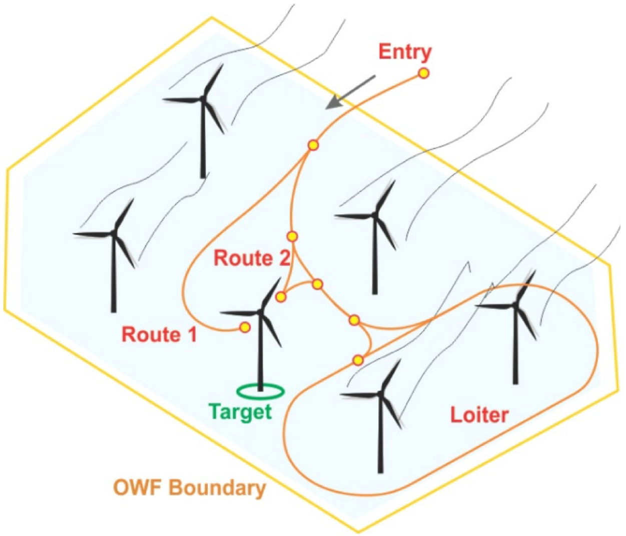


Fig. 9 Example of planned approach routes to target WTG and loiter track

5.5 Path planning implementation

Flight Phases 1–3 each require the planning of feasible flight paths which recognize the vehicle's operating limits (especially its fuel resources and environmental conditions) and given geospatial boundaries, such as obstacles, prohibited airspaces, or protected terrain which should not be overflown. We also assume that the mission sets time constraints for the drone to arrive at the target destination and that the use of fuel should be minimal. These requirements create an interesting optimization problem for the path planner. Furthermore, time-dependent factors, such as wind or the activation/deactivation of prohibited airspaces, require the flight paths to be referenced in time, as well. Hence, a feasible and optimal take-off time for a given round-trip flight must be found. The above-stated planning problem was solved by the implementation of a global trajectory planner, which is based on the Probabilistic Roadmap Method (PRM). The roadmap approach features a one-time assembled collection of waypoints connected by feasible path segments, which forms a reusable search graph for the planning algorithm. The flight path segments from shore to the OWF are restricted to existing helicopter waypoint network presented in Section 1. To allow for more detailed planning at the OWF and on the mainland around the take-off location near Emden, quasi-random sampled waypoints are used to create a dense search graph. The resulting roadmap is shown in Fig. 8 in yellow color.

The implemented planning algorithm is designed to consider spatio-temporally varying wind fields obtained from medium-range weather forecast models to recognize anticipated changes in wind conditions which affect the flight time and fuel consumption depending on the take-off time and choice of flight route. A detailed description and performance analysis of the planning algorithm is published in [21]. Fig. 8 shows an example trajectory found by the path planner for a simulated transport mission. The spatio-temporally varying wind fields for the planning area used by the planner are provided by the DLR Institute of Atmospheric Physics in [22] for the time between Oct. 30th and 31st 2023 (midnight to end of day). The time resolution of the wind field is 3 h and the outward flight to the OWF as well as the return shall be conducted during this timeframe. The algorithm finds optimal trajectories at 4:30 am on Oct. 31st and calculates different trajectories for outward flight and return. For this planned path, the assumed available fuel was not exceeded, while the choice of other take-off times resulted in longer flight times and a violation of the fuel resources.

6 Interaction of the drone with the wind farm

Flying a highly automated drone in a complex environment such as a wind farm requires that the drone be provided with as much live information as possible about the environment in the wind farm. This information will enable the drone to adapt to the wind farm's operations and weather conditions via automated processes such as motion planning. The drone's path planning could use current weather information and the current operating conditions of the WTGs to generate routes through the wind farm and approaches to the landing pad that guide the drone through zones with as little wind turbulence as possible. Information about air traffic or maritime traffic in the wind farm can let the drone plan routes to avoid this traffic, and information about the availability of loading pads in the vicinity can help to quickly reschedule for an emergency landing in exceptional situations. Since full automation of drones and entire wind farms is currently very much in its infancy, this concept assumes that the drone's ability to act is rather conservative. This means that serious decisions about the wind farm and the drone itself will be delegated to a human if possible, but the human will make his decisions based on processed data from the drone and the wind farm. For the interaction of the drone with the wind farm, this means that the drone should receive as much data as possible, but the data flow will only be of a purely informative nature. It will therefore not initially be possible for the drone to have a direct influence on the operational processes in the wind farm, e.g., to shut down wind turbines independently or to issue recommendations for ships or other air traffic to take evasive action.

6.1 Telemetry and data links

The individual mission phases impose different requirements on the performance or data transfer rates of deployed data links. Phases 1, 3, and 4 require high data rates with relatively low latency, since a large amount of data have to be transferred between the drone and the wind farm, as well as the ground station. This includes weather information, which is used area by area for planning, and finally the result of the planning, the flight path, which is to be sent to the control room for approval. Since the drone is very close to the launch site in Phase 1 and very close to the OWF in Phases 3 and 4, a relatively short range but high bandwidth data link can be used in these phases. Phase 2, on the other hand, does not require much data exchange as the drone will only be sending out data for rudimentary monitoring by the ground control station during its flight. Since future drone operations envision a fully automated drone with emergency procedures that are also automated, manual intervention in the drone's flight controls (e.g., by a safety pilot) is not envisioned. Therefore, all transmission paths and data that would be necessary for manual guidance of the drone (complete flight status data, real-time transmission of data, and transmission of the pilot's control inputs to the drone) are omitted. Instead, the drone should broadcast its position, airspeed, and altitude at low-frequency intervals, so that monitoring of the flight is possible similar to the flight monitoring performed by an air traffic control center. Since the flight time of the drone to the target may be hours, the ground control station should be able to obtain an adjustment of the drone mission via the data link by transmitting short and robust signals. For example, to be able to persuade the drone to turn back or divert to another landing site before fuel resources have been unnecessarily consumed. The data link may therefore have relatively high latency and relatively low bandwidth to transmit data. Since the flight path can be over 100 km, the data link must instead have a very high transmission range. The selection of a suitable data link also depends on how well it can be integrated into the drone. It must be considered that the drone is very limited in terms of payload, installation space, and energy resources (power supply). In addition, the system must be robust enough to ensure reliable communication even in bad weather, higher mechanical stress, or even fluctuations in the power supply. Therefore, the following requirements can be added for the data link:

- Lowest possible system weight
- Lowest possible power consumption
- Robustness against weather conditions and hard landings
- Robustness against fluctuations in energy supply
- High reliability.

Finally, also the non-recurring costs must be regarded (even though standing back against safety) as they affect the economic benefit of the drone operation and can be an important influence, e.g., for satellite link communication. In the following, different solutions for the data link are presented and their advantages or disadvantages are discussed.

6.1.1 Public mobile network

In recent years, the mobile network in the *German Bight* has been expanded and is still being expanded. To enable the use of the mobile network for workers on working platforms far from the coast, more and more of these platforms are equipped with cellphone antennas. Cellular networks are present at the launch site and surrounding area onshore and within the 12 mile zone around the German coast. The above image of Fig. 10 shows a calculated cellphone network coverage (hatched area on the right), which is achieved on the one hand by the antennas located onshore and realized on the other hand by providers specialized on onshore cellphone service (hatched areas in center and left). The areas near the coast shaded in yellow show the cellular coverage achieved by the onshore-based antennas. The coverage was determined on the basis of the antenna locations and a simulation of the radio range in [23]. The exemplary flight path of a drone from the mainland to the *Hohe See* OWF shown in blue in Fig. 10 is largely covered by cellular networks. The installation of further mobile radio systems on platforms in the North Sea will allow the existing gaps to be closed in the foreseeable future. In any case, wind farm operators have now signed contracts with various mobile phone providers to enable their employees to make phone calls and use broadband Internet on site. The LARUS research project (Situation Support for Maritime Emergency Operations by Unmanned Aerial Systems) has already tested the operation of drones over the Baltic Sea using the mobile communications network for communication and control of the drone from an onshore-based ground station. Important findings from this testing reported in [24] are that seamless and, at the same time, broadband reception over the LTE network is possible if as many of the existing frequency bands as possible can be used. Since the various frequencies can heavily fluctuate based on the position, fast switching between the frequencies must be made possible to minimize data loss.

Overall, it can be assumed that an available mobile communications network enables data transfer with low latency and large bandwidth. The costs for receiving or transmitting devices and for data transfer are relatively low. Providers may offer preferred services for large business customers and the specific use-case, which increases the reliability of the data link but also drives up costs. If multiple cellular providers are present at the same time or overlap, multiple contracts may be needed and the receiving device must be designed to be able to quickly switch between providers. Mobile receiving devices are very compact and are therefore easy to integrate. Power requirements are generally low. Possible disadvantages of using the cellular network are that it is publicly accessible and, therefore, connections to the drone or wind farm could in principle be disrupted or even used as an entry point for cyberattacks on the drone or wind farm infrastructure. This requires appropriate protection of the data transfer. Likewise, the data transfer can be disrupted by problems at the respective provider, which could be the case, for example, in the event of large-scale power outages near the provider's server centers or if the network is overloaded by too many simultaneous users. One way to avoid these problems would be to set up redundant island solutions for the cellular network, which ensure local information exchange, so that the drone and the wind farm can communicate even if there is no continuous connection to the mainland. Another way to address this issue is that the operations could be re-planned or terminated as long as this data link is not used for safety–critical communication.

6.1.2 High frequency data link

A dedicated data link provides an alternative for communication to the drone that is independent of other radio systems. For high transmission rates at short range (up to a few kilometers), radio links in the 433 and 920 MHz frequency range have become established for drone applications. Omni-antennas, i.e., antennas broadcasting equally in all directions, are usually used, so that an area around the antenna can be covered without gaps. The disadvantage of this method is the relatively short range. It would therefore be necessary to install appropriate radio antennas at relatively short intervals along the flight routes and connect them to ensure continuous communication. The range may be extended by directing the datalinks (see below). However, this goes with a loss of flexibility.

Hardware for the radio link is relatively inexpensive and installation is also simple. To increase robustness and transmission, powers can be chosen as necessary. However, both of these measures may require approval from the German Federal Network Agency, which results in relatively low one-time and ongoing costs.

6.1.3 Satellite communications

Communications satellites cover much of the earth, especially areas far from the Polar Regions, so it is expected that satellite links can be established from any part of the transport route. The satellite systems that can be used for the use-case (e.g., Iridium) are in relatively high orbits, so latency is expected to be very high. SpaceX's *Starlink* satellite network, which is still being developed, uses much

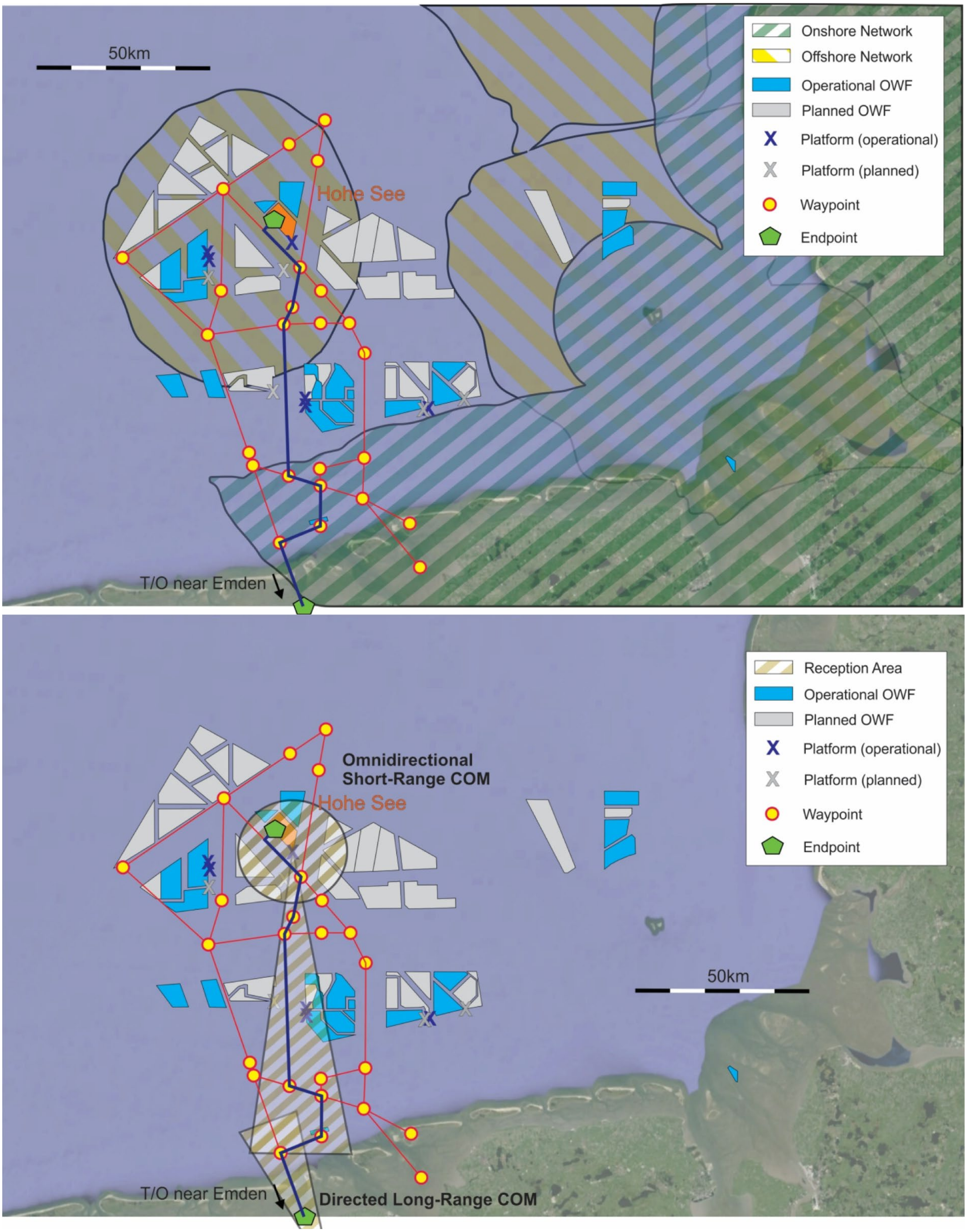


Fig. 10 Above: communication concept using currently available cell phone networks. Below: Communication using directional antennas for long-range data exchange and omnidirectional antennas for short-range communication

lower orbits, which significantly reduces latency. From 2023, *Starlink* will offer the use of the network for aircraft. The receiving equipment used is relatively large and heavy, and the cost of receiving equipment is very high for monthly usage [25]. The transmission of data can be disturbed by environmental factors (clouds, solar winds, atmospheric reflections, etc.) and attitude of the antenna on board of the drone. The absence of shadowing mountains or large structures at sea favors communications. The power requirements of satellite antennas are low to moderate. Data transmission services are relatively costly. Significant additional costs can be expected, especially if data are to be transmitted preferentially.

6.1.4 Directional antenna with LoRA WAN communications technology

Special directional antennas (e.g., Yagi-Uda antenna) could achieve ranges of several hundred kilometers with relatively low transmission power. Long-Range (LoRA) Wide Area Network (WAN) communications technology is specifically designed for very long-transmission ranges at relatively low transmit power, and robustifies the data exchange at the distance against noise and other interference that would otherwise prevent correct reception of the data.

To be able to achieve a particularly high range (of a hundred kilometers or more), the antenna must be mounted very high up (100 m and more) due to the curvature of the earth and must have a very pronounced directional characteristic (only a few degrees). This means that the antenna can only cover a very narrow, but long sector. To ensure communication to the drone during the whole route, two scenarios are possible:

a) Selection of a particularly straight route

If a particularly straight route can be chosen, the directional antenna can be placed in extension of the route ends. Since the straight route is relatively narrow, the directional antenna can also be chosen to be very narrow. Alternatively, multiple antennas with slightly different orientations can be used to cover a wider area. This concept is shown for the example route in the lower part of Fig. 10. Here, radio in the wind farm and near the launch site is enabled by mobile radio or omnidirectional radio link (hatched circle) and radio along the straight-line flight sections is enabled by appropriate directional antennas using the LoRA technology (hatched cones). The advantage of the method is that any number of drones can be reached with one or few antennas. The disadvantage is that the requirements for the transport route are very restrictive, or the establishment of new routes automatically entails the installation of additional antennas.

b) Tracking the drone through an antenna tracker

Since the drone is always transmitting its position, this can be used to determine the direction with which the antenna must align itself with the drone to ensure optimal reception. This allows antennas with extremely narrow beam angles to be used. The disadvantage is that a separate antenna must be kept for each drone, and the connection is susceptible to GNSS failure or a once lost connection may not be easily restored.

Procurement of the antenna and receiver components is comparatively simple and inexpensive. Installation at high altitude, on the other hand, is more difficult, especially if the mast has yet to be procured and erected. Also, the installation in the OWF and with maritime conditions might increase the costs of such systems significantly. As the drone transmits data, it would need to be equipped with powerful antennas, possibly resulting in high system weight and power consumption. Operation of the system, on the other hand, is inexpensive, with costs likely to be incurred for approval of operation by the German Federal Network Agency.

6.2 Data exchange between OWF and drone

Offshore wind turbines have their own control electronics to which the sensors and actuators of the turbine are connected. The sensors are used, among other things, to measure weather conditions (wind strength, direction, and temperature) to be able to adjust the operating state of the turbine (e.g., blade position and position of the nacelle) accordingly. This operating data can be made available to third parties via one or more interfaces. The supported communication protocols are specified by the supplier of the WTG but can be extended by additional ones via gateways. The data update rate is fixed by the installed sensors and control electronics of the WTG. Therefore, it is likely not possible for the drone to set an update rate for the requested data. In larger wind farms, a higher level farm-wide system is typically set up to monitor and control the WTGs. It then makes sense to use the operating data of this system to keep the number of interfaces as small as possible. In most of the communication protocols commonly used in this field, the available data scope is recorded in data point lists. These lists contain all available signals, their addressing, and meaning to allow data retrieval. Especially, worth mentioning is the heli-hoist stop which offshore wind turbines with hoist areas can adopt by request of the control room. In this mode, the turbine control system prepares the turbine for the arrival of a helicopter and enables it to safely drop off loads or personnel. The pilot of the helicopter is notified of the correct operating mode of the system via a green lamp, which is clearly visible on the nacelle. The status of the lamp can be queried digitally via the turbine's data interface and thus also made available to a drone. If the wind farm is equipped with a helicopter landing deck, a weather station is installed on the OSS, which collects and provides aviation weather data for the helicopter crews. This includes data on precipitation levels, visibility, and cloud bases. These data can be used for the drone to ensure, for example, that safe operating limits are maintained.

To increase flight safety, it would make sense for the corresponding faculties to provide additional information about the occupancy of their landing area. Such information would be useful if the drone needs to approach an emergency or alternate landing site and is looking for a nearby but vacant site to do so. This can be preplanning data derived before the flight, or, to include update statuses (e.g., 'in-use') this can be combined with live data exchanged during flight.

In addition, aeronautical and maritime infrastructure, such as ADS-B and AIS, could be installed at the wind farm and the data fed into the data interface. Thus, the wind farm could take over the task of data collection redundantly to the drone, which on the one hand protects against the failure of the equipment on board the drone and on the other hand enables the drone to include ships and aircraft in the wind farm in the planning process at an early stage, since this information would otherwise only be available when the drone enters the reception area. Tables 1 and 2 in the Appendix show the necessary set of data with recommendations for sending frequency and units.

Table 2 covers already available data in the OWF *Hohe See,* which needs to be pre-processed before sending (e.g., to calculate the mean wind), while Table 3 covers additional information which needs to be generated and processed by new infrastructure.

Operational data of the wind turbines, traffic, and environmental data on the current and past wind and weather situation are important information to the drone's automatic planning algorithms. Thus, to allow path planning even before the beginning of the mission, the data should be made available to the drone at all times and not only while being in direct vicinity of the OWF. An interface to the OWF available via public internet with secure gateways to the drone and drone provider would solve this requirement.

Some of the data necessary for the execution of the drone flight changes so slowly that a constant query via the data connection does not seem reasonable. This includes, for example, the geo-positions of the WTGs, which will practically never change. These data can be made available to the drone offline in the form of a database. Should the data change from time to time or need to be supplemented, the database could either be manually flashed on the drone by the ground staff of the drone provider or there is an automated process in which the drone compares its database on the ground with an online available database before take-off and applies the corresponding updates.

The following list contains data that should be kept in the form of a database on the drone:

- Signals (data point lists) and designations of WTGs, OWFs, and sensors such as weather stations.
- Geo positions of the WTGs.
- Dimensions and position of the landing area, as well as its maximum carrying capacity and related technical data.
- Geo positions and designations of airspaces (restricted areas, etc.) and sea areas (e.g., boundaries of wind farms and safety zones around locations).
- Geo positions and designations of emergency or alternate landing areas (e.g., helidecks).
- Geo positions and designations of waypoints or flight paths which should always be used for route planning. This includes enroute waypoints from the mainland to the OWF as well as special waypoints which are to be used for entering the OWF; fixed waypoints or flight paths within the OWF may also be defined.
- Geo positions and designations of waypoints or flight paths which are intended for exceptional cases, e.g., a holding pattern can be defined in or around the OWF, where the drone flies in and waits for the continuation of the mission in an energy-saving manner.

6.3 Implementation of the data interface between the drone and the OWF

The telecontrol protocols and system architectures used for data transfer in EnBW's wind farms are designed for robust and secure plant automation and are hardly known and therefore not used in the drone industry. Therefore, it is necessary to use a protocol for data exchange that can be easily implemented on both sides and also guarantees the necessary data security and robustness. A possible protocol for this task is Message Queuing Telemetry Transport (MQTT), which has proven itself for years in home automation, enjoys an easily accessible developer community and is increasingly used in industry. MQTT uses a publish-subscribe architecture. To receive data, the drone registers as a client with a broker (subscribing) and subscribes to data by naming the signal name (topic) of one or more desired WTGs. The wind farm is registered with the broker as a publisher and publishes the data on the topics. The broker takes over the distribution of the data. To keep the data traffic low, there is no acknowledgement of receipt by the thread, and instead, a complete data set is transmitted at defined intervals (e.g., at least every minute) to replace lost or erroneous data. This method is known in computer science as fire-and-forget, a term from military jargon. This behavior can be used to ensure that no buffered data are sent again, so that up-to-date data are always available.

The broker for the flight test presented in Chapter 7 implemented a routine which would send empty fields in MQTT messages if no new data were received between transmit intervals or specified data values indicating corrupted or invalid data were received. This implementation allows the drone to automatically detect whether received data are valid and may be used to trigger further actions. Figure 11 shows the concrete data flow between the drone (left) and the OWF (right). The upper half of the figure presents the data flow according to the concept and the lower part presents the implementation of the concept into the flight experiment. To use the data from the OWF's protocol with MQTT, a gateway is required that converts the protocols accordingly. The gateway's dataflow management is designed to prohibit any external access on functions of the wind farm to prevent unintended exposure of critical systems to the public. The converted data are then provided to an MQTT-broker to which the drone's MQTT-client can subscribe. By swapping roles, the data flow can be reversed, and communication from the drone to the wind farm can be established if needed. In particular, when using the Internet to transmit data (e.g., using the public cellular network) between the broker and the drone, the data must be protected from unauthorized use and the interfaces must be protected from unauthorized access. This can be done in several ways. First, the MQTT protocol offers Transport Layer Security (TLS) encryption, and second, the connection itself can be protected by a Virtual Private Network (VPN) tunnel. TLS encrypts the data itself and therefore makes it usable only for certain clients that have identified themselves properly beforehand. In addition, MQTT offers security mechanisms in which it is possible to specify which users have write access to selected topics (Fig. 12).

7 Onshore flight experiment

7.1 Experiment overview

The onshore test trial is intended to test the concepts and ideas created under real conditions. The results can be used to derive improvements and possible problems for real deployment. Because not all real conditions can be set during the test trial, there are some prerequisites and deviations to the real deployment. The first deviation is the terrain. The flight test does not take place in an offshore, but in the onshore wind farm *Schwienau II & III* located in Lower Saxony, Germany.

Fig. 12 Unmanned technology demonstrator *superARTIS* flying in Schwienau

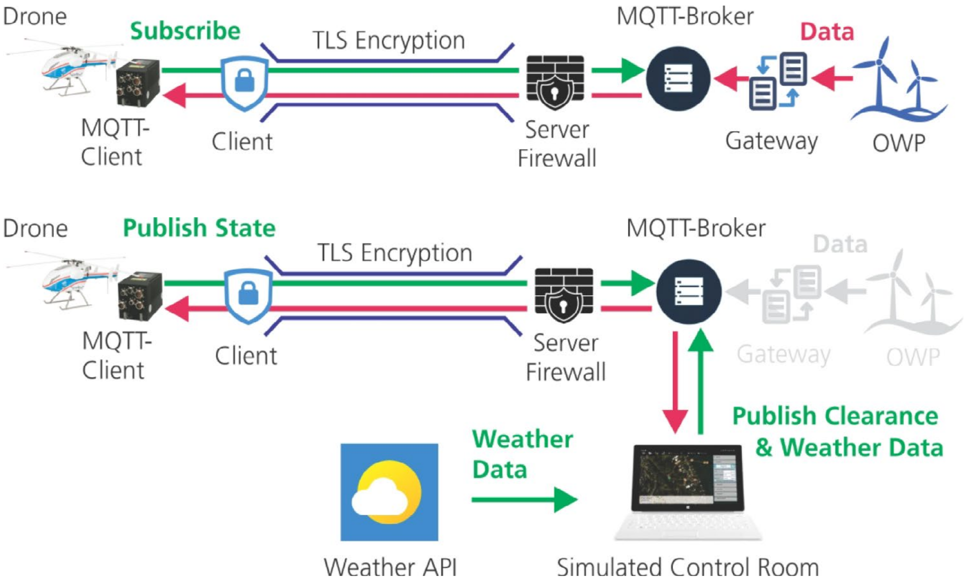


Fig. 11 Above: MQTT-based setup to exchange data between OWF and Drone to receive wind turbine data. Below: communication between drone and simulated control room and weather API for the flight experiment

In the test flight, moreover, the wind turbine will not be stopped remotely. To stop a wind turbine, a technician is on site. In addition, no hoist signal exists on the onshore wind turbines, since these turbines do not have a hoist area. The hoist signal is simulated by software. Similarly, no additional weather station exists in the wind farm. The weather station is simulated by a software which requests and provides the weather data from a weather API.

The communication between service process, drone provider, drone computer, control room, and wind farm is reduced to interaction between the drone computer, a simulated control room, and the wind farm (see lower half of Fig. 11). In addition, many messages are omitted in the communication flow. The communication for request, status, and confirmations of the flight in between control room, drone computer, and the wind farm take place. As well as the measured values that are transmitted from the wind farm. In addition, the flight is assumed to be error-free and emergency transmission protocols are not implemented. The communication takes place with an implemented MQTT interface between drone and wind farm as described in Sect. 6.3.

An MQTT-broker is set up for the test flight and can be reached via public Internet. Data from the wind farm are published to the broker via a gateway. This communication is read-only to prevent the wind farm from being influenced. All communication is encrypted using TLS and secured using user credentials.

The control room is simulated through custom-developed software connecting to the MQTT-Broker. The software is designed to indicate incoming requests from the drone to the operator, who then can accept or reject the request. The decision is sent to the drone where it is processed by the drone computer. In addition, the control room software displays all the weather data from the simulated weather station and all data received from the WTGs.

To simulate additional wind farm infrastructure, a server is set up that runs programs in addition to the simulated control room. One of these simulates a weather station by retrieving real-time weather information via a weather API. Just like the virtual control room, the programs publish their data on the MQTT-broker, which then get forwarded to the drone.

The flight tests will be conducted using DLR's unmanned research helicopter Autonomous Research Testbed for Intelligent Systems (*superARTIS*, see [26]) as the transport drone. The *superARTIS* shown in Fig. 11 is *a swissDrones Dragon 50* helicopter with two intermeshing rotors and a maximum take-off mass of about 85 kg. The maximum wind speed for *superARTIS* operation is at 11.1 m/s. The rotor configuration allows a maximum payload capacity of up to 45 kg including fuel. The *superARTIS* will be equipped with a transport box to simulate the transported cargo and a communication interface to the wind farm and flight avionics to control the motion of the drone for parts of the planned test. The avionics and communications setup are described in the following.

The drone is equipped with a Raspberry-Pi companion computer which is connected as client to the MQTT-Broker via a mobile cellphone dongle. The Raspberry-Pi subscribes and receives the incoming messages from the MQTT-Broker and feeds them via Ethernet connection to the experimental mission manager. The mission manager holds several preplanned flight paths from a starting location of the experiment to a defined target WTG and is able to dynamically choose a flight path based on the received information on the wind situation and WTG condition as well as the received clearance of the control room to proceed with the flight. The chosen trajectory is shared with the *superARTIS* flight controller to execute the mission.

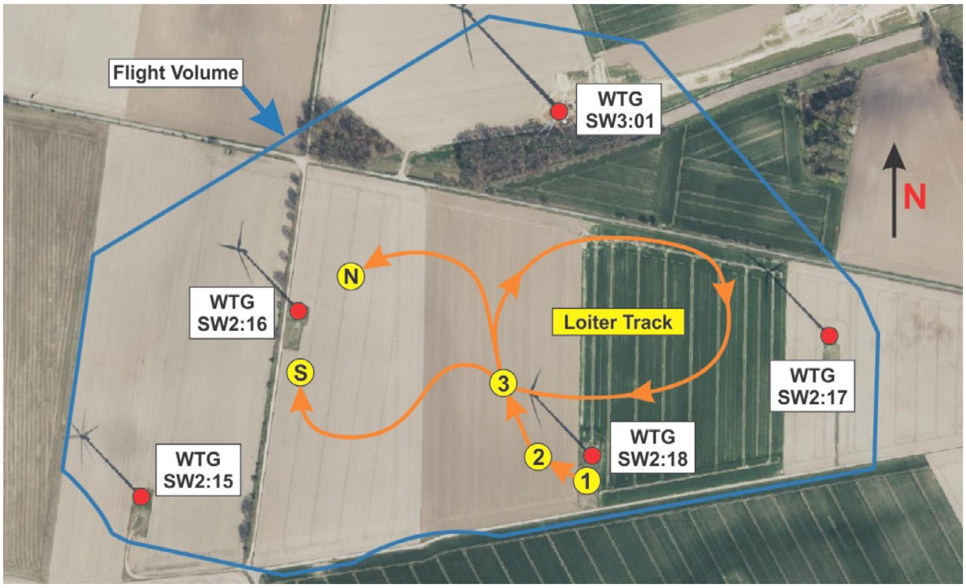
The received information on wind farm, weather station, and control room are shared via Mavlink protocol with a modified version of the QGroundControl, an open-source ground control station mainly developed to communicate with autopilot software like *PX4* or *ArduPilot* [27, 28].

Figure 13 shows a top view on the wind farms *Schwienau II* (WTGs indicated with SW2 in the South), and *Schwienau III* (WTG SW3:01 visible in the North). Due to boundary conditions set by rulemaking authorities, the presence of highly frequented roads and housing in close proximity, as well as visual line-of-sight (VLOS) requirements, the size of the flight test area had to be limited to the boundaries of the wind farm (blue line in Fig. 13).

The orange lines and yellow circles in Fig. 13 outline the planned vehicle trajectory and their entry or exit points, respectively. The procedure for the example transport mission of the flight test is as follows. The mission starts with an automatic take-off of *superARTIS* at Point 1 inside the wind farm and the establishment of an altitude of about 90 m above ground level while traveling horizontally to the experiment starting point marked as Point 2. Then, the control of the vehicle is taken over by the experimental flight management system, which collects information on the weather situation and operational condition of the wind farm via the MQTT interface. Once all information is available, it issues a request for permission to approach WTG SW2:16 of the wind farm while steering *superARTIS* from Point 2 to Point 3.

Point 3 serves as a decision point within the flight experiment. If Point 3 is reached before permission is given or WTG SW2:16 is not hoist-ready, a loiter track is initiated and carried out. As soon as the correct shutdown of the WTG is indicated by the simulated heli-hoist status and permission is given by the simulated control room, the flight management system ends the loiter track at Point 3 and commands either a northern approach route to the Exit Point N or a southern approach to the Exit Point S. The route is

Fig. 13 Top view of the planned flight test in Schwienau. The orange lines mark planned flight trajectories and the yellow circles mark entry and exit points between the trajectories



chosen based on the current attitude of the WGS's nacelle, so that an approach through the WTG's rotor disk is avoided. Note here that the rapidly changing wind information is not used as a factor for the approach route decision to keep the decision as deterministic as possible. Once the decision is made, the flight management submits the trajectory to the flight controller to be executed. Once arrived at the trajectory's exit point, the *superARTIS* is put into a hovering condition and taken over by the drone pilot which concludes the experiment.

7.2 Experiment results

The flight experiment took place on October 10th 2023. For the experiment, the approached WTG SW2:16 and WTG SW2:18, which served as the take-off and landing location, where switched off by a maintenance team just minutes before the start of the flight test campaign and to minimize the loss of revenue due to down times. The WTGs can be switched off in two ways: the activation of an installed maintenance mode, which automatically locks the turbine rotor and nacelle in place, but unfortunately also switches off the telemetry of the WTG, or the manual wedging of the turbine which ensures locking of rotor and nacelle, but does not affect the broadcasting of telemetry. The manual wedging requires a person to set the locks by hand which takes time for preparation and execution. This option was chosen for WTG SW2:16 to simulate the heli-hoist mode. Before wedging the nacelle, it was manually positioned to a heading of 325° which enforced the southern approach route and the approaching *superARTIS* to be well clear of the rotor blades. Just before take-off, the WTG SW2:18 was put into the maintenance mode, which caused disruption of its telemetry for the time of the experiment.

After both involved WTGs stopped, the experiment started with a check flight to familiarize with the environment and to ensure that safety–critical systems are ready for automated flight. Then, three simulated transport missions were conducted. The flown trajectory (based on the GNSS track) of the second flight, flown at a constant height of 105 m above ground level, is shown in Fig. 14, which adapts the yellow entry and exit points of Fig. 13. For better visibility of the trajectories, the entry and exit points have been slightly shifted within the figure. The different colors of the trajectories indicate the active state of the mission state machine.

In all flown scenarios, the transition into the loiter track was provoked by intentionally delaying the approval for the final approach. Instead, the approach clearance was given right after the loiter track was initiated. The according transition of the state machine is indicated by a change of trajectory color in Fig. 14. After the loiter track was finished, the *superARTIS* entered the final approach phase from Point 3 to Point S.

After the automatic mission ended at Point S, the *superARTIS* was manually flown by the BVLOS pilot to approach WTG SW2:16 up to a distance of 30 m. The awareness of the horizontal separation between *superARTIS* and WTG to the BVLOS pilot was only based on GNSS data of *superARTIS* and the known position of the WTG tower. As the GNSS position accuracy is depending on satellite reception and may cause horizontal uncertainty of several meters, a minimal approach distance of 30 m was chosen and also a visual guidance by a spotter located directly at the WTG

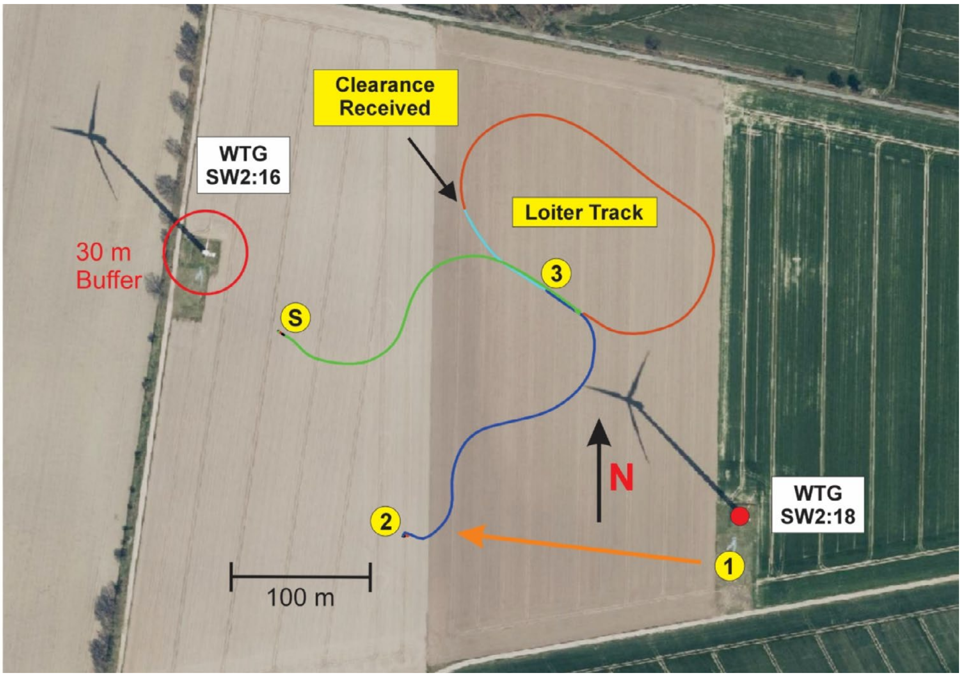


Fig. 14 Trajectories of manual approach of second flight experiment

was established to prevent any unintended approach below the 30 m boundary.

The GNSS ground track of the approach maneuver following the simulated mission is shown in Fig. 15. The ground tracks of all experiments involving a close approach on WTG SW:16 reveal that the minimum distance of 30 m was never violated, while the radio communication between spotter and BVLOS pilot leads to good situational awareness.

The evaluation of the exchanged data during all flight experiments was driven by two considerations. The data reception was analyzed in a gap analysis to evaluate the connection quality and the ability to seamlessly receive data of all WTGs located in the wind farm *Schwienau II & III* (SW2 & SW3). The plausibility of the received data was obtained from plots of the received data over time and comparison of weather data (wind speed and wind direction) with the operational data of the WTG (rotor rpm, nacelle heading) as well as the comparison of these data points between the different WTGs. The WTGs are of same type in SW2 and of same type in SW3 and are located with a few hundred meters between each other, and thus, it can be assumed that the recorded wind situation and resulting operational data should be in good agreement. For the data evaluation, all data received via the MQTT protocol onboard the *superARTIS* were immediately stored with according timestamps in an SQL-based database.

Figure 16 shows the data gap analysis for all WTGs in SW2 and SW3 obtained from the data available in the SQL-database. The black lines actually consist of dots, each indicating that the MQTT-client received data from the broke for the respective WTG. MQTT-data are published in fixed intervals once every minute. Comparison of the MQTT datapoints of each WTG, reveal matching gaps in which no data of any WTG were received. These gaps align well with the overall test protocol and can be explained with the fact that *superARTIS* or the MQTT-client software were not running during these times. Two relatively large gaps only seem to occur for SW2:18. These gaps are highlighted with a red rectangle and a question mark in Fig. 16.

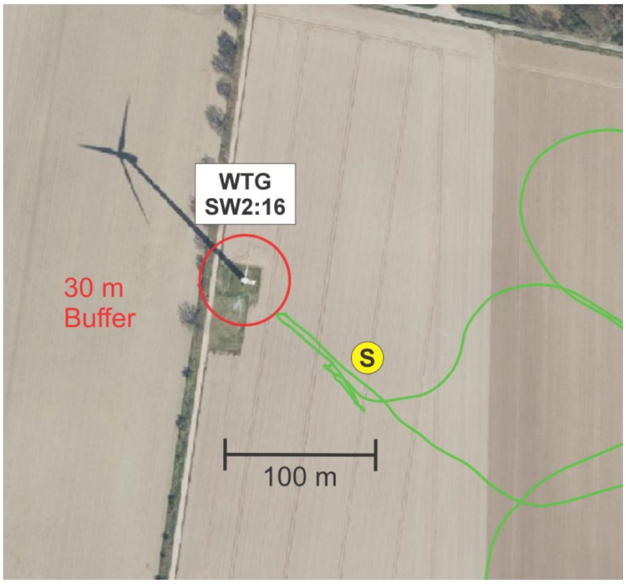
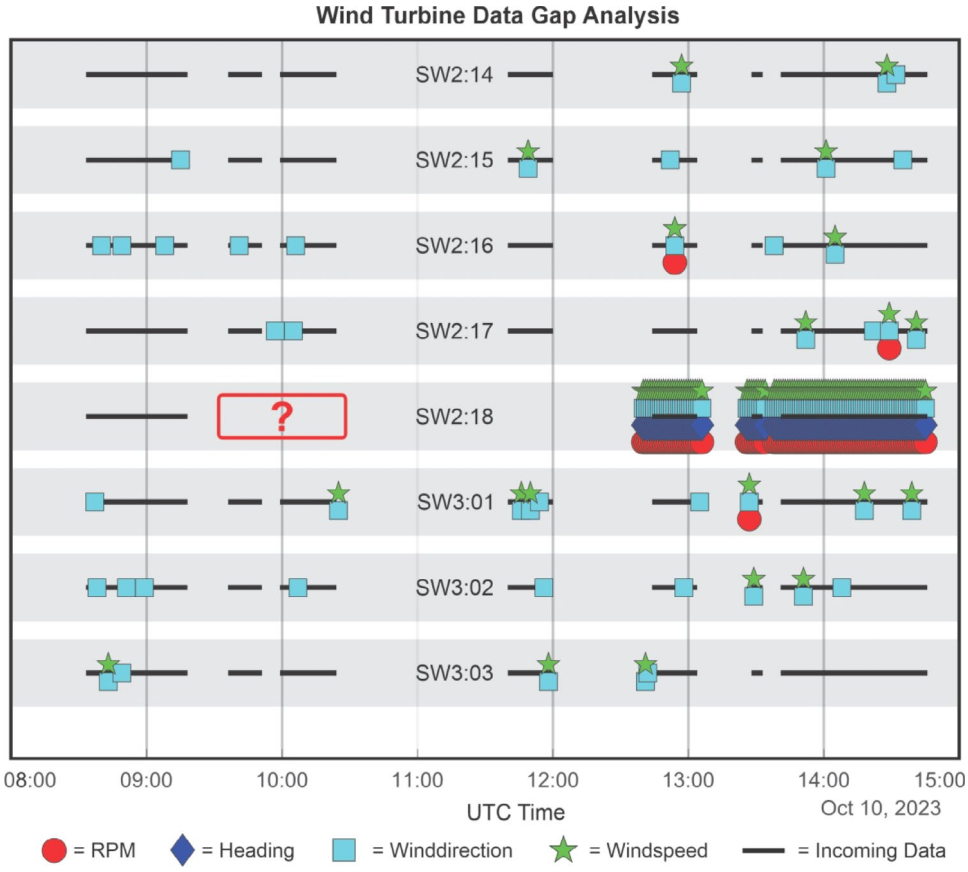


Fig. 15 GNSS ground track of simulated transport mission of second flight experiment

Fig. 16 Data Gaps, black lines mark incoming data from the MQTT-broker. The red rectangle highlights a time in which no MQTT-data of WTG SW2:18 was received



The different colored symbols in Fig. 16 mark events, in which MQTT-data were received, but did not contain valid data for the WTG rotor rpm, the nacelle heading, the wind direction, and wind speed. This method reveals that some data points are sporadically unavailable, most prominently the data measurements of the wind sensor (wind speed and wind direction). It is also visible that SW2:18 emits no valid data starting from 12:30 UTC which can be easily explained with the change of the operating status of that WTG into the maintenance mode.

Figures 17 and 18 show polar plots of the received data on nacelle heading and wind situation, respectively. The radius of the plot in Fig. 17 serves as the time axis to visualize the timely development of the heading for each WTG. Figure 18 uses the radius to display the wind speed. For the WTGs in *Schwienau II*, the plots show an overall good agreement of nacelle heading and wind direction, with the exception of the stopped WTGs SW2:16 (heading intentionally set to 325°) and SW2:18 (heading locked in maintenance mode). The nacelle direction and wind data change rapidly over the plotted time of several hours. In contrast to this rapid change, the information provided by the WTGs in *Schwienau III* does not change at all during the same period of time resulting in a straight line in the nacelle plot and a single dot of data in the wind plots. Also, none of these provided single data points match the wind situation or nacelle heading of the WTGs in *Schwienau II*.

7.3 Experiment discussion

The EnBW technical staff kindly provided insight into the technical setup of the OWP *Hohe See* and the setup of the onshore wind farms *Schwienau II & III*. A comparison between both systems revealed that the OWP infrastructure for data collection and transmission greatly differ from onshore infrastructure regarding the hardware for data collection, the network to transfer the data, and the used data protocols. In general, it can be stated that requirements regarding robustness and reliability are much higher for offshore infrastructure when compared to onshore infrastructure. Among the reasons for this difference are the much greater size, monetary value, and energy production capacity of offshore wind turbines which makes use of high-grade components more reasonable. Furthermore, offshore turbines are able to closely supervise the turbines to detect damages and wear and tear in an early stage to align the costly maintenance and repair process accordingly.

In general, the provided data of the turbines in *Schwienau II & III* are only used to determine energy production over long periods of time and to provide some of the

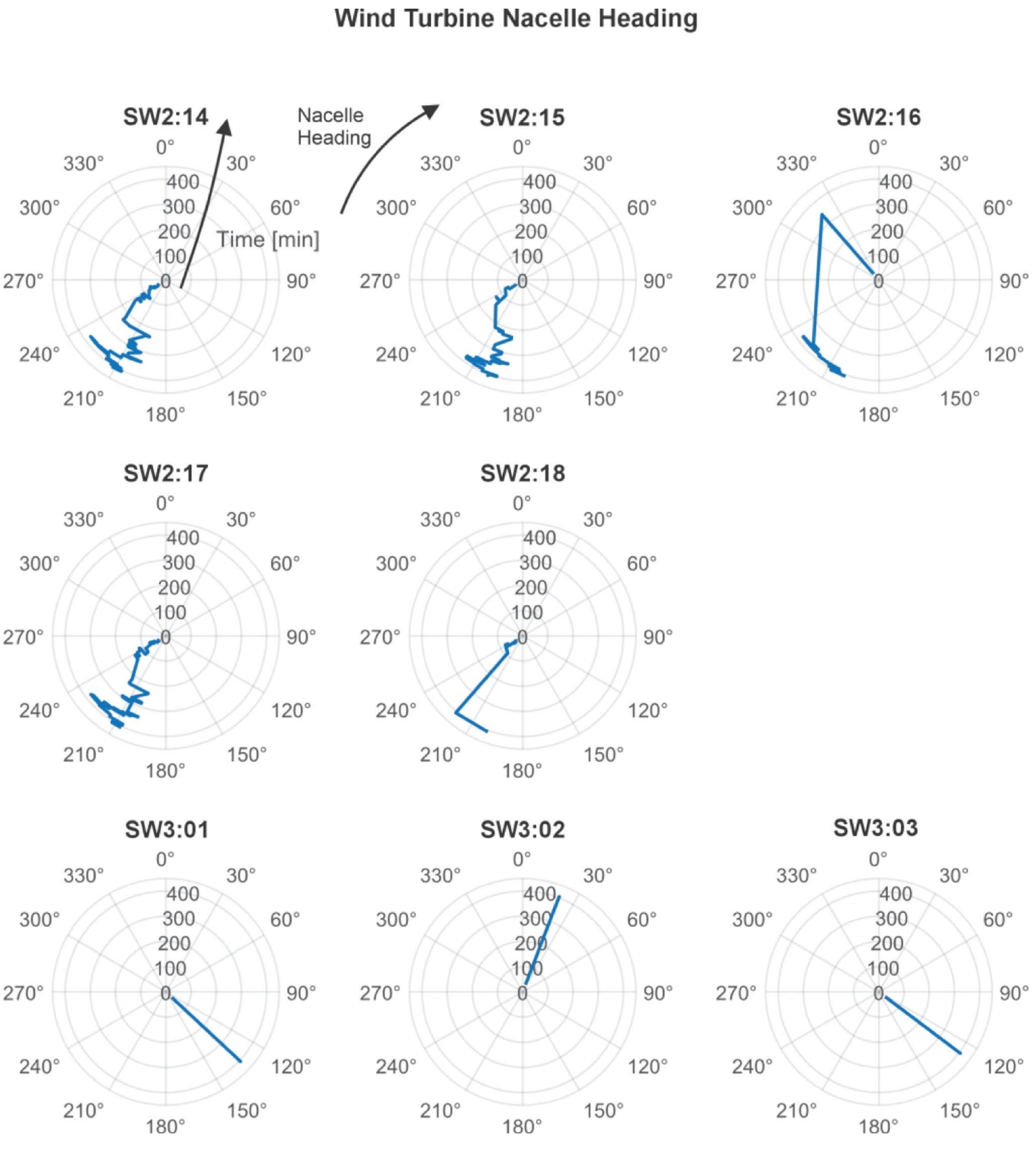


Fig. 17 Nacelle heading

data to the public via an available online tool or cellphone app, as part of public relation. Therefore, it is tolerated that single measurements of the turbine are not available from time to time and even over a period of several hours or days. The observed data gaps in the provided data can be explained with a missing synchronization of the sensors to the MQTT-client which caused new sensor data to arrive too late for the next data broadcast of the MQTT-broker. The data provided by the turbines in *Schwienau III*, which did not change over time, were probably caused by stalled or falsely terminated data connections within the local wind farm network.

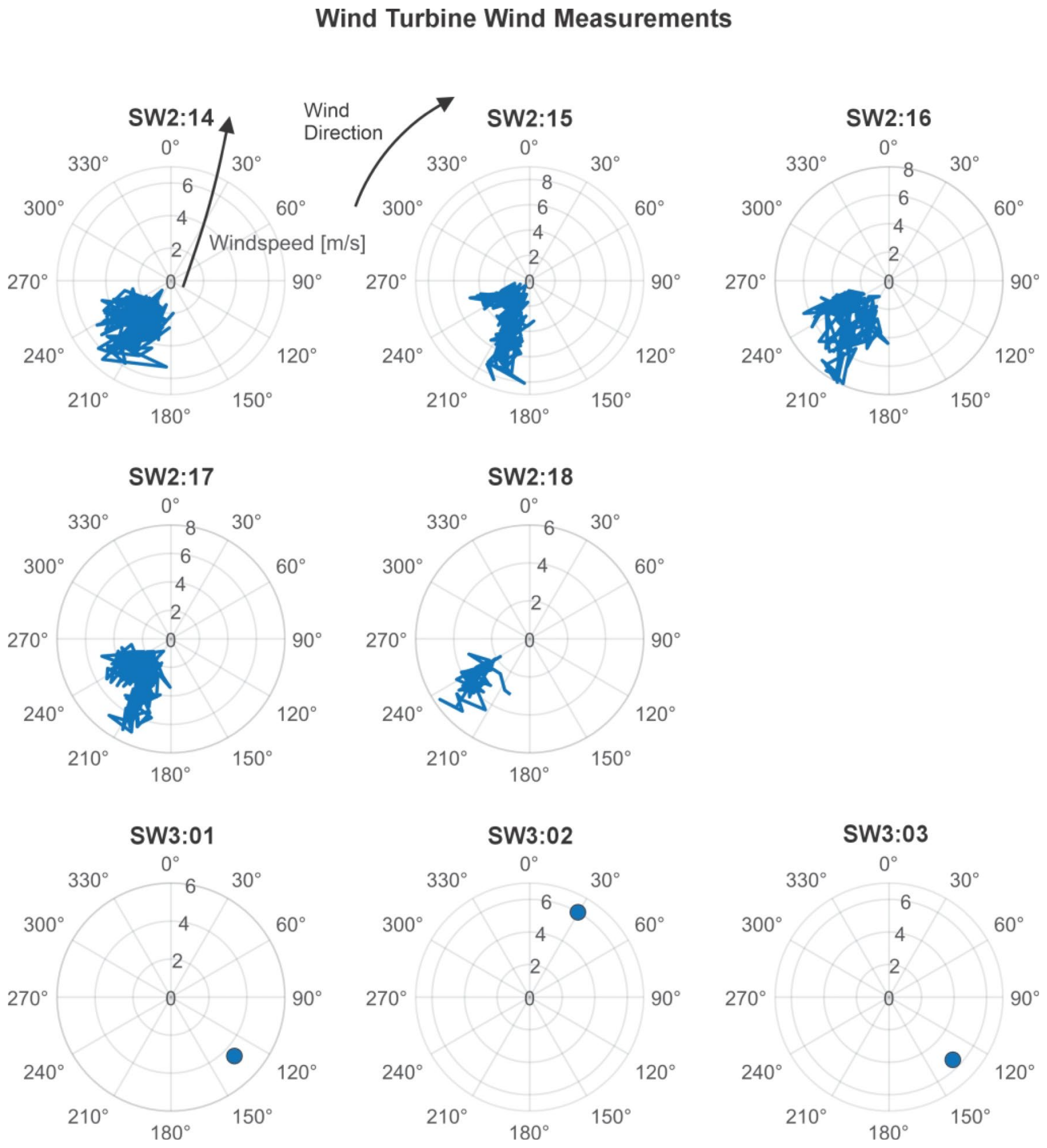


Fig. 18 Wind measurements

For energy production, the relation between heading of the turbine nacelle and wind direction is relevant. As a result, the heading and wind direction information may not be referenced with respect to true north and the obtained values might differ between the turbines as observed in *Schwienau III*.

The investigation of the data gap marked by the red rectangles in Fig. 16 could not provide any reason for the missing data of SW2:18. For every single wind turbine, the client has to emit an individual subscription message to the MQTT-broker. Each subscription message contains a request for either all available or specified data of each turbine. It is possible that the subscription message was not correctly received or processed by the MQTT-broker.

In summary, it can be stated that the data infrastructure provided by *Schwienau II & III* poses a lot of limitations to automated drone transport. Information on operational condition and weather is not consistent due to data gaps or inconsistencies as observed for the heading or wind direction reference. The relatively low update rate of 1 min is likely not sufficient to quickly gain a full picture of the operational state of the wind farm especially if single data points are missing during an update.

The created communication setup to receive and process data of *Schwienau II & III* can be easily adapted to other wind farms if they provide an MQTT-broker with a connection to the internet and an interface to the wind farm network. Thus, it is intended to conduct another flight experiment wherein the communication with an offshore wind farm will be investigated. The planned flight experiment will use the same communication hardware and software as described above, but hooked up to a multicopter drone instead of the *superARTIS*, which greatly reduces inherent complexity and operational risks of offshore flights. The flight is expected to take place in the EnBW offshore wind farm Baltic 1 in the Baltic Sea and in the summer time of 2024. The experiment will focus on evaluation of quality and robustness of the data exchange, and thus, it is not planned to recreate the automatic flight of *Schwienau II & III*.

8 Conclusion

The project Upcoming Drones Windfarm (UDW) between the German Aerospace Center (DLR) in collaboration with the German energy provider Energie Baden-Württemberg AG (EnBW) researches the advantages and possible implementation of future cargo transport for maintenance of offshore wind farms, which may be improved through the use of drones. The drones need to be integrated into the maintenance process for the OWF and the maritime environment consisting of the wind farm, ship traffic, and offshore transport infrastructure such as a waypoint network.

The presented research places a special emphasis on the communication between drone and OWF during its transport mission. For identification of necessary interfaces for exchange of information, a simplified mission context for the drone transport was generated and used to embed a fictitious transport to the operational OWF *Hohe See*. The OWF *Hohe See* is located in the *German Bight* and is operated by EnBW.

The fictitious mission to *Hohe See* can be divided into four mission phases, each with different requirements to the exchange frequency and type of data. Three alternatives to implement a communication network have been elaborated and discussed: use of satellite communication, implementation of a radio network with long-range datalinks, and use of public and private cell phone networks.

The aspect of drone communication to the wind farm's control room to synchronize the transport mission with the operational condition of the OWF as well as with the governing maintenance process has been evaluated in more detail. The main outcome is a sequence of information to be exchanged between the entities to maximize the efficiency and awareness of the transport mission.

The data transfer via cell phone network has been chosen to be used for the exemplary implementation of the communication concept in a flight experiment in onshore wind farms *Schwienau II & III* located in Lower Saxony, Germany. The successfully conducted flight experiments proofed the elaborated interaction between drone and wind farm based on the wind farm's operational conditions and supervision through the wind farm's control room. The flight test also revealed that sensor and data information of the considered onshore wind farm was not reliable as data packets were corrupted or not distributed at all. Data distribution systems of offshore infrastructure are designed to fulfill stronger requirements on data distribution quality and availability, thus requiring re-evaluation of the data exchange in an offshore flight experiment.

Ongoing work focuses on the repetition of the communication experiment in an EnBW's offshore wind farm *Baltic 1* in the Baltic Sea. Also, the communication concept validated by flight tests can be further developed in various ways. Within the project UDW, it can be used in other work packages to concretize simulations of the full cargo transport mission. Furthermore, the concept may serve as an example to concretize the logistical network around the drone transport mission, which is also a part of the UDW project.

Also, the results may be used to update EnBW's requirement documents for future OWFs to enable them for future drone transport missions. Nevertheless, it must be seen as a first step to enable the drone interaction with the OWF. Aspects as system security or failure and redundancy will be relevant aspects to be further detailed in future work.

Appendix

See Tables 1, 2 and 3.

Table 1 Exchange of messages between stakeholders of drone mission

Message	Transmitter	Recipient
Initial request	Service process	Drone provider
Planning & coordination	*Planning & coordination by service process, control room and drone provider*	
Pre-flight checks	*Pre-flight checks by drone provider, drone, and drone pilot*	
Cyclic information exchange	Drone & Drone pilot	Drone provider
Cyclic information exchange	Drone & Drone pilot	OWF
Final launch request	Drone & Drone pilot	Control room
Final launch confirmation	Control room	Drone & Drone pilot
Cyclic information exchange	Drone & Drone pilot	Control Room
	Drone flies to OWF and reaches OWF	
Request for WTG stop	Drone & Drone pilot	Control room
	Drone flies to the WTG	
Hoist signal confirms WTG stop	OWF	Drone & Drone pilot
	Drone lands on the WTG	
Goods delivered	Drone & Drone pilot	Drone provider
	Drone flies back	
Logout from the location and OWF	Drone & Drone pilot	Control room & OWF

Table 2 Required data issued by OWF

No	Value	Unit	Precision	Rate	Remarks
1	Mean wind speed (last 10 min)	m/s	1/10	~10 s	Wind measurements conducted at this interval
2	Maximum wind speed (last 10 min)	m/s	1/10	Every minute	Evaluation of gustiness using the dataset of No. 1
3	Mean wind direction (last 10 min)	degree	1	~10 s	Determine direction of inflow
4	Mode of operation	Flag	1	~10 s	Verify WTG is in hoist mode for landing
5	Rotor RPM	1/min	1	Every minute	Evaluate induced turbulence of other turbines
6	Heading of nacelle	degree	1	Every minute	Calculate landing spot
7	Air temperature	°C	1	Every minute	Verify minimal operational limits of mission
8	Air pressure	hPa	1	Every minute	Verify minimal operational limits of mission, requires a weather station
9	Visibility	m	1	Every minute	Verify minimal operational limits of mission, requires a weather station
10	Ceiling	m	1	Every minute	Verify minimal operational limits of mission, requires a weather station
11	Precipitation	mm	1	Every minute	Verify minimal operational limits of mission, requires a weather station

Table 3 Additional information provided by OWF

No	Value	Unit	Precision	Rate	Remarks
12	Landing surface available	Flag	–	every minute	Landing surface clear of objects and ready for landing
13	Number of ADS–B clients	–		every minute	
14	List of position and altitude of ADS–B clients	Nx3 list (Latitude, Longitude, Altitude Alt) of N clients in degree, degree, m	(10e–6, Lat, Lon), 1/10 for altitude	every minute	
15	List of velocity and course of ADS–B clients	Nx2 list (velocity and course) of N clients, m/s, degree	1/10	every minute	
16	Number of AIS clients	–		every minute	
17	List of position of AIS clients	Nx3 list (Latitude, Longitude, Altitude) of N clients in degree, degree, m	10e–6	every minute	
18	List of velocity and course of AIS clients	Nx2 list (velocity and course) of N clients	1/10	every minute	

Author contribution AD—Wrote the main manuscript and contributed with the main mission concept and integrated the flight control algorithms SC—Project Management, contributed chapters presenting stakeholder analysis JW—Wrote the MQTT code on drone side, contributed to MQTT communication concept JD—Contributed to chapters on data links and reviewed the interaction concept between drone and wind farm DH—Implemented MQTT protocol on wind farm side, contributed by reviewing MQTT chapters JJ—Provided references and material covering procedures and standards for helicopter operations in German Bight and at EnBW, contributed to Introduction and general concept presentation TB—Detailed the exchanged data between drone and wind farm and generated Tables 1—3.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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