# PAYLOAD DELIVERY TO OFFSHORE WIND TURBINES USING UNMANNED HELICOPTERS

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Numerous wind turbines have already been installed offshore for green and sustainable electricity production. Also new wind parks with steadily increasing dimensions are currently installed along many shores in many countries. However, the long-term and smooth operation of each wind turbine - under often harsh and challenging environmental conditions - requires frequent inspection and maintenance work. The technical crew, repair equipment, and spare parts are often provided by vessels traveling for several weeks within the wind parks. Nevertheless, shortages of replacement parts and time-consuming ship cruising and docking can create substantial downtimes. Here, unmanned industrial helicopters with high payload capacity can deliver various repair items to reduce down-times and minimize losses due to repair work. This presentation is based on the ADD2Wind research program where an unmanned, autonomously flying helicopter is being used for payload delivery to the nacelle of a wind turbine. Initial flights have been demonstrated and recorded in June 2023 showing the performance of the aircraft during approach, delivery, and homing flight. Beside video sequences from different perspectives real flight data is being analyzed. To achieve flight permission, the unmanned helicopter is equipped with an emergency flight termination system (FTS). The payload section is used with an electric winch to lower the payload on the nacelle without landing the helicopter on the nacelle.

## INTRODUCTION

The maintenance of offshore wind turbines is challenging in multiple ways. Transportation of the repair crew and required spare parts is often time consuming and floating warehouses are both energy- and labor-intensive. Warehouses onshore are much less cost intensive and can be operated 24/7. But the transportation of spare parts to the offshore wind turbines on the other hand is also challenging. Within the research project “Airborne Drone Delivery to Offshore Wind Turbines” ADD2Wind the focus lies on an unmanned, industrial, autonomously flying helicopter with an integrated winch to transport and deliver spare parts to the nacelle of an offshore wind turbine while staying in hover flight during the delivery process and return to the shore afterwards. Initially flights were tested on a simulated platform described in section 2 where various flight data is shown. Various sensors onboard the helicopter have been used to monitor the payload delivery. This

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includes inertial sensors, forward and downward looking cameras, and laser scanner to receive accurate distance information. These initial flights were followed by BVLOS flights described in section 3 and flights to a real wind turbine with delivery of a payload sample on its nacelle described in section 4. Section 5 summarizes the research program and shortly describes the process to achieve flight permission both in Switzerland (CH) and Denmark (DK).

**Figure 1. Offshore wind park in Denmark.**

Figure 1 shows part of an offshore wind park at the cost of Denmark. The ADD2Wind research project is based on an industrial, unmanned helicopter equipped with a flight control system (FCS) allowing autonomous lift-off, path following, and landing.

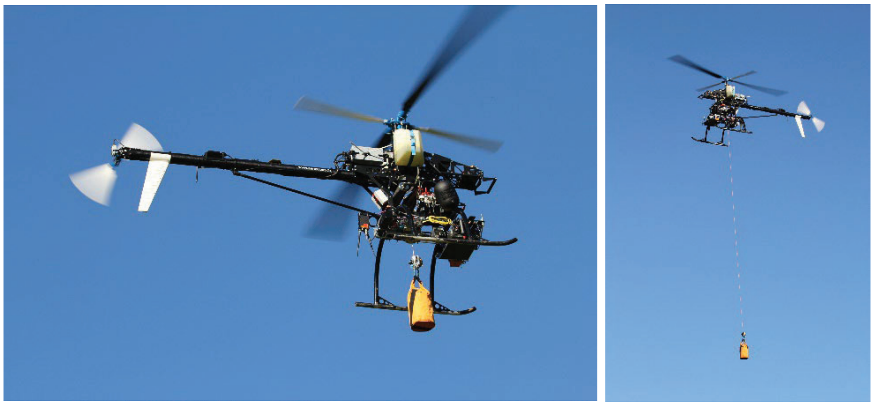

**Figure 2. Aeroscout Scout B1-100 UAV helicopter equipped with payload and payload winch.**

Data communication is based on a long-range WLAN network during the flight allowing video feedback to the ground control station (GCS) where the operators handle both aircraft and payload. The unmanned helicopter Scout B1-100 UAV produced by Aeroscout GmbH as shown in Figure 2 with its classical main and tail rotor configuration provides multiple benefits in this operation compared to manned helicopters as well as muti-rotor UAVs/drones. Besides the vertical lift-off and landing capability and the benefit to hover above the nacelle during payload delivery the helicopter as a substantial wind gust robustness due to its rapid helicopter swash-plate configuration which decouples in windy conditions the main rotor plane from its body movements, allowing stable and precise hovering. Multi-rotor UAVs have to adjust the complete airframe to stabilize in windy conditions. In addition, during cruise flight, the fuel consumption is considerably reduced compared to multi-rotors UAVs and an optimal traveling speed can be selected. Some of the main specifications for the Scout B1-100 UAV helicopter are given in Table 1. Further flights are planned with the

Scout B-330 UAV which provides a flight endurance up to 3 hours and a payload capacity up to 30kg.

Once the wind park and its individual wind turbines have been mapped in its spatial spreading, repeated flights can be pre-programmed and flights can be repeated very accurately for each individual wind turbine even under low visibility conditions. This is also a major advantage compared to manned helicopter flights. Furthermore, flights at night are possible. With a future flight endurance up to 3 hours, even offshore parks far away from the coast can easily be reached.

**Table 1. Aeroscout Scout B1-100 UAV main specifications**

| | |
|---|---|
| Main rotor diameter | 3.2m |
| Main rotor speed | 860 rpm |
| Maximum Lift-off weight | 85kg |
| Gasoline engine | 100ccm (2 stroke) |
| Fuel tank | 10l |
| Payload capacity | 18kg |
| Flight endurance | 1.5h |

The Scout B1-100 UAV helicopter has been equipped with a payload winch allowing to lower the payload on the nacelle of the wind turbine and hoist the release mechanism back after delivery. In emergency situations, the payload connection can be cut off from the ground control station command. Multiple video and data links allow instant monitoring of the flight status, the payload delivery process, and situational awareness.

## 2. TESTING EINVIRONMENT WITH A SIMULATED NACELLE

In order to prepare and test the various components of the UAV installation, including data and video links, payload winch, laser scanner, forward and downward looking cameras, transponder, flight termination system, manual backup and manual override, hovering precision, delivery time required, as well as team coordination, the nacelle of a wind turbine has been built as a simulation model shown in Figure 3.

**Figure 3. Aeroscout Scout B1-100 UAV helicopter hovering above a simulated nacelle.**

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During the flights, videos as described above are used to document the payload delivery. The center of the nacelle has been marked with a visual pattern which allows to measure the precision of payload delivery. The fence of the simulated nacelle also should reflect the real situation of the wind turbine which is also surrounded by the protection railing. In general, the simulated nacelle was built in smaller scale making the payload delivery even more challenging.

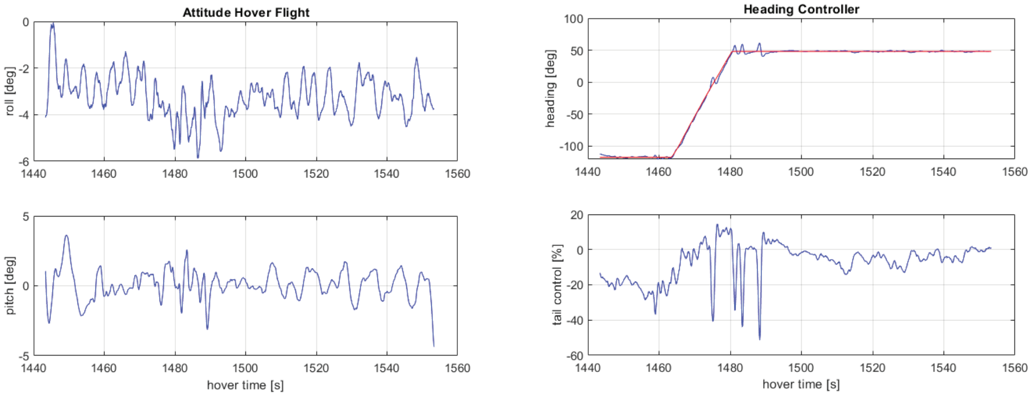


**Figure 4. Attitude control during payload delivery**

From the flights above the simulated nacelle the data sequence during the payload delivery has been extracted. The payload delivery took about 2min to lower the payload bag and to hoist the mechanism afterwards. Figure 4 shows the attitude data of the helicopter during the delivery process. Depending on wind gusts, minor changes in pitch and roll angle reach 2..5°. For the heading angle it is relevant to point the helicopter to wind direction. Also wind gusts have a significant influence on the tail control signal up to 40…50%.

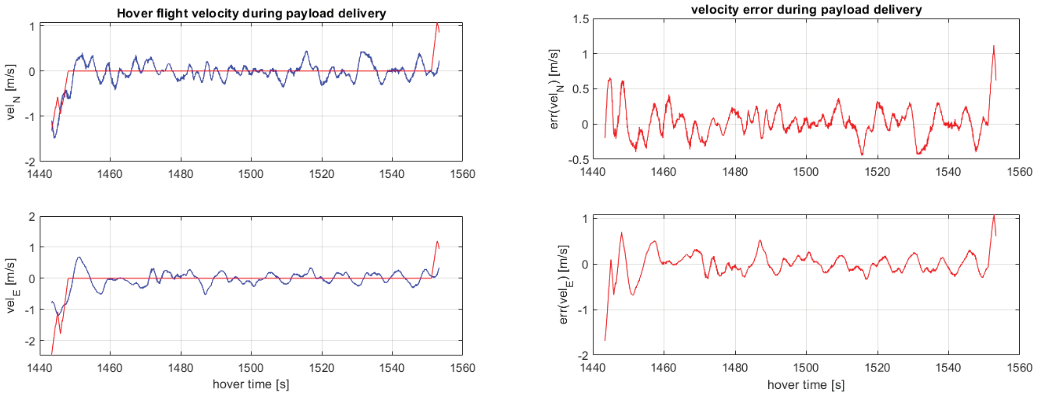


**Figure 5. Velocity control during payload delivery**

In Figure 5 the absolute UAV velocity, the reference velocity, and the velocity error in north and east direction are shown. Even under windy conditions, the velocity error remains below 0.2…0.3m/s which allows a highly precise payload delivery with minor position changes.

Figure 6 shows the absolute flight position during payload delivery. Once the target position is reached the reference position remains constant. At this instant also velocity control changes to position control of the aircraft. The cartesian standard deviation achieved is approximately $\sigma_{north} \approx 0.51$m and $\sigma_{east} \approx 0.86$m. This rough position accuracy gives an initial estimate of payload delivery under real conditions. However, it is noted that the final payload delivery accuracy also depends from the payload movements. Once the payload is let down, the payload can start to swing below the aircraft. In order to avoid these oscillations, the payload winch works rather fast to place the payload once the target position has been reached. All this testing could well be done with the simulated nacelle on ground.

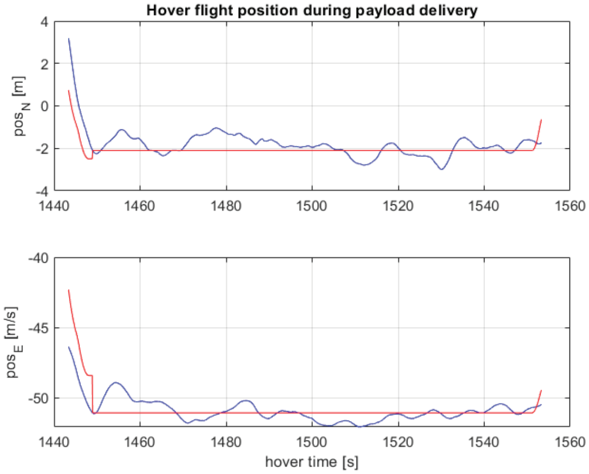


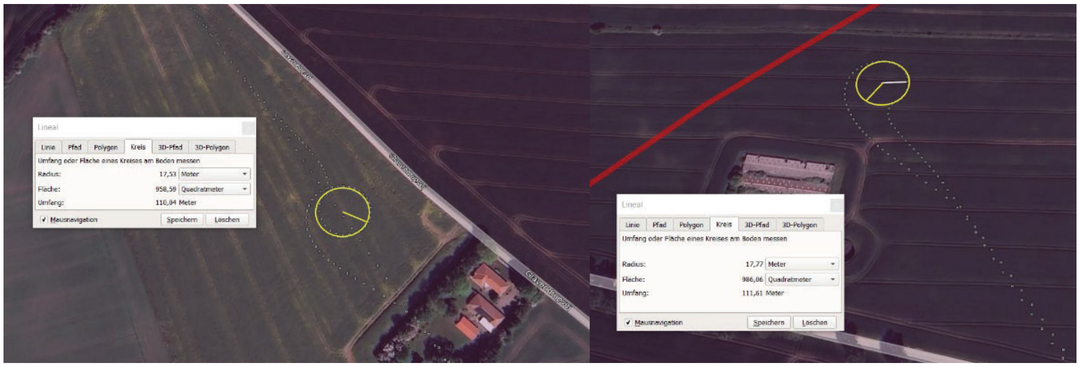
**Figure 6. Position control during payload delivery**

## 3. TEST THE AIRCRAFT FOR FLIGHTS BEYOND LINE-OF-SIGHT (BVLOS)

The intention of the ADD2Wind project is to finally demonstrate the payload delivery to offshore wind turbines. This will require to perform flight beyond line-of-sight (BVLOS) and to achieve the related flight permission. This section summarizes the BVLOS flights performed in Denmark in June 2023.

**Figure 7. BVLOS flights performed in Denmark**

The BVLOS flights took place from Hans Christian Andersen Airport in north direction with distance of approx. 5km as shown in Figure 7. During the departure flight several flight circles have been added in order to test and validate the video and data link performance under all around conditions from the aircraft to the ground control station. During the flight more than 86 signals have been recorded. The flight took place at 100m altitude above ground. The number of GPS satellites in view were about $\#_{GPSsat} \approx 20$. The recorded standard deviation in latitude and longitude position error was achieved at $\sigma_{lat/lon} \approx 1.2 \ldots 1.3$m. The cruise flight took place at $v_{cruise} = 10$m/s.



Umfang oder Fläche eines Kreises am Boden messen
Radius: 17,53 Meter
Fläche: 958,59 Quadratmeter
Umfang: 110,04 Meter

Umfang oder Fläche eines Kreises am Boden messen
Radius: 17,77 Meter
Fläche: 986,06 Quadratmeter
Umfang: 111,61 Meter

**Figure 8. BVLOS flights including flight circles and return flight**

The flight circles as shown in Figure 8 have been performed with a radius of $r_{cruise} \approx 18\text{m}$ and can clearly be seen in the heading data. The same radius was used when starting the return flight. The flight trajectories for departure and return flight are within a distance of five meters which was well covered. The return flight was preprogrammed as a direct line within the designated airspace.

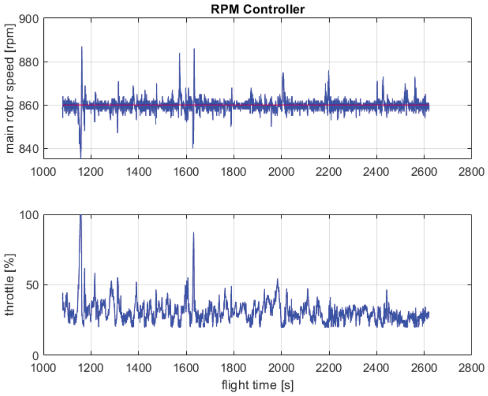


**Figure 9. RPM control during BVLOS flight**

Figure 9 shows both the main rotor rpm signal and the gas input. After the initial hovering period when all instrumentation is checked before departure, the maximum gas setting is reached to initiate the climbing process. While in cruise flight the power consumption drops significantly to 35…40% which is a major advantage of the classical helicopter configuration.

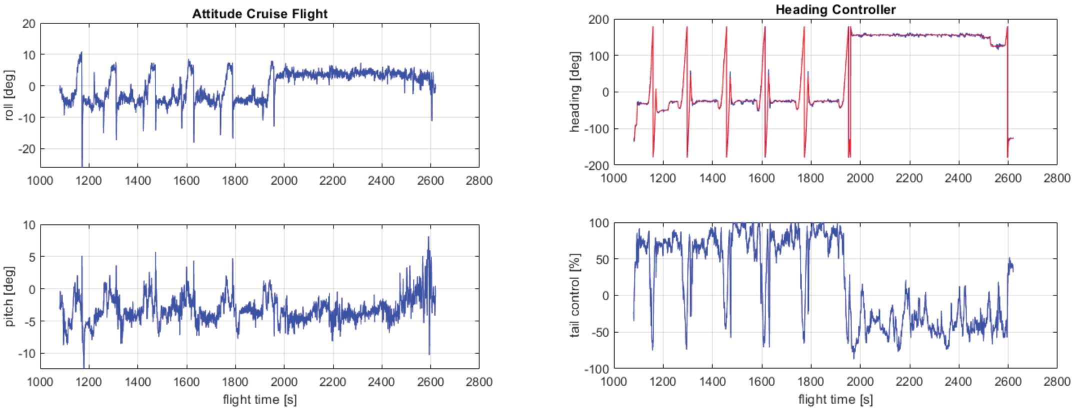


**Figure 10. Attitude control during BVLOS flight**

Figure 10 shows the attitude angles during the flight. While the pitch angle is more or less contant, the roll angle shows the slope of the aircraft during the flight circles. Also the influence from the side wind can be seen in the roll angle which changes from -5deg in departure flight to +5deg in return flight. The side wind also affects the tail rotor control which can reach 100% control authority in departure flight and -60% in return flight.

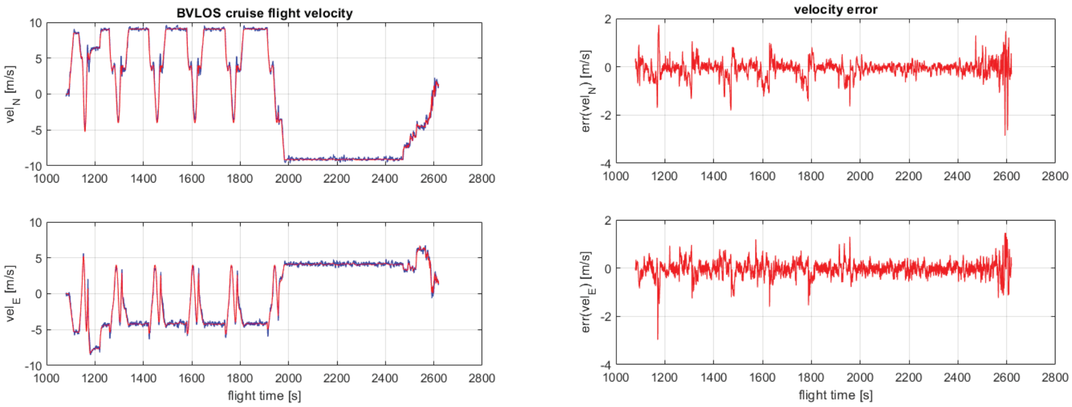


Figure 11. Velocity control during BVLOS flight

The velocity data is shown in Figure 11. Again, the flight circles in departure flight are visible while the return flight is at constant north and east velocity. The standard deviation of the velocity error is only $\sigma_{vel,north} \approx 0.35$m/s and $\sigma_{vel,east} \approx 0.31$m/s but will also depend on the wind conditions in general.

## 4. DEMONSTRATION OF THE PAYLOAD DELIVERY AT WIND TURBINE

End of June 2023 the payload delivery to a wind turbine has been demonstrated and recorded from various camera perspectives.


ADD2wind

Airborne Drone Delivery to
Offshore Wind Turbines

Figure 12. Demonstration video of payload to a wind turbine

The video as shown in Figure 12 has been processed by Anders la Cour-Harbo, associate professor and director of drone research lab at Aalborg University, Denmark. Anders is also initiator and head of the ADD2Wind research project.

The delivery of the payload was shown on a real wind turbine with its nacelle at 100m above ground. The unmanned helicopter did approach the wind turbine from behind. The downward looking camera was used to position the helicopter above the nacelle and to monitor the process of payload delivery. For safety reasons during initial flight tests the blades of the turbine have been fixed. This would have allowed the aircraft to also increase forward speed in case of sudden engine power loss or other irregularities. In addition, a camera on the nacelle could monitor the approach of the aircraft towards the nacelle. Finally a small electrical drone could record the flight following the main UAV.

**Figure 13. Approach and payload delivery with the Scout B1-100 UAV helicopter (courtesy Aalborg University, Drone Research Lab)**

The flight termination FTS82-H Mark II, system has been provided by Loxar and was installed to immediately stop the ignition of the gasoline engine in case of an uncontrollable situation. In Figure 13 the approach of the nacelle as well as the process of payload delivery has been captured from the accompanying camera drone.

**Figure 14. Retracting the release mechanism after payload delivery (courtesy Aalborg University, Drone Research Lab)**

After delivery the payload on the nacelle the small release mechanism has been retracted before starting the return flight as shown in Figure 14 (small item below the helicopter in left-side image).

## 5. SUMMARY AND ACKNOWLEDGEMENT

The previous sections describe the step-by-step procedure to successfully demonstrate the payload delivery to a wind turbine using an unmanned, autonomous helicopter. The work was provided within the ADD2Wind research project, led by Anders la Cour-Harbo and compliments go the complete research team both in Denmark and Switzerland.

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A considerably amount of work was done to finally achieve flight permission. The submission to the CAA includes:

- SORA (Specific Operation Risk Assessment),
- OM (Operations Manual),
- ERP (Emergency Response Plan),
- ConOps (Concept of Operation),
- checklists, and
- AFM (Aircraft Flight Manual).

It is expected that unmanned robots can play a significant role for offshore wind parks for inspection, maintenance, and repair in near future. A combination of different sizes of UAVs can even increase the flexibility of required services.

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