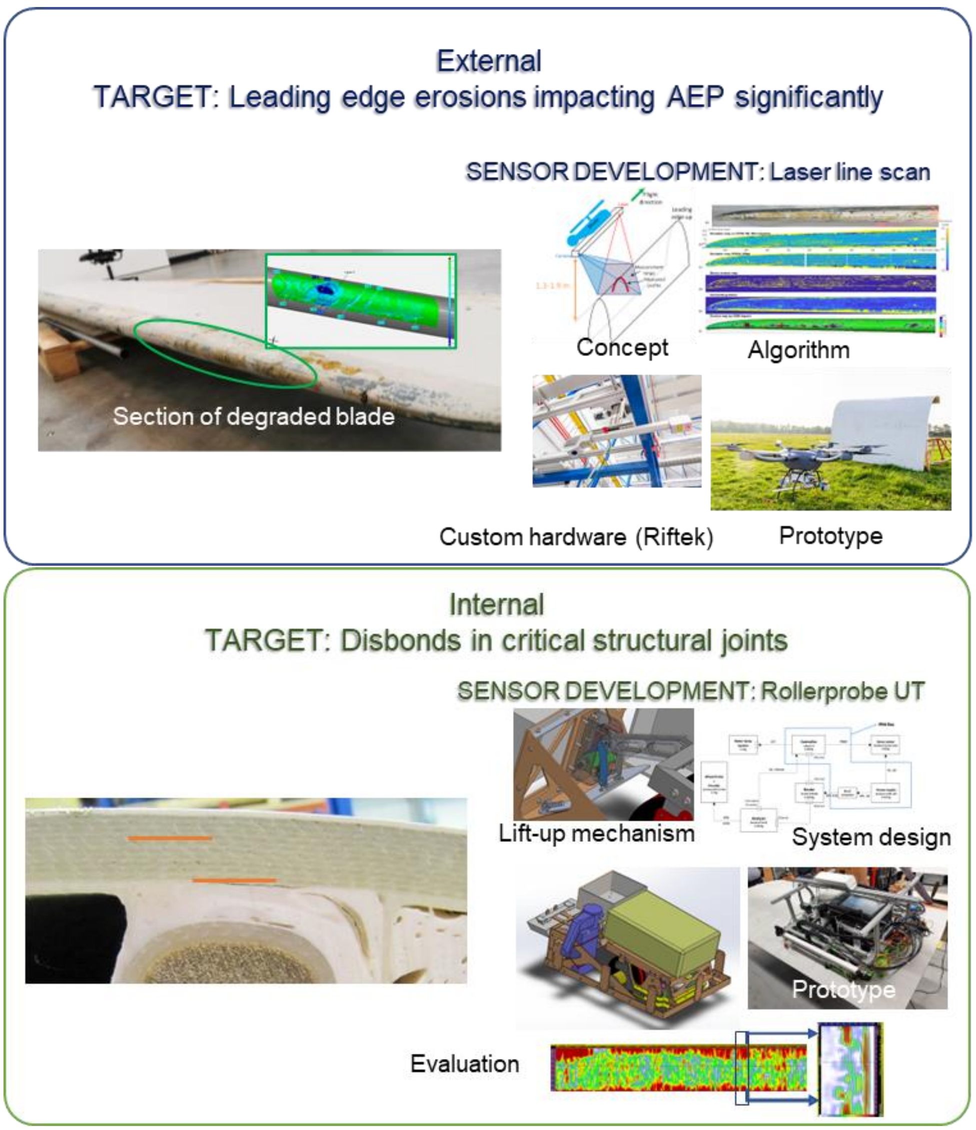
WP 1 Sensor Package Research

WP1 leader: TNO

Participants:

- NLR
- TU Delft
- Dutch Terahertz
- Hanze
- HZ Robotics
- Inholland
- DfW



Introduction

Within the work package 1, research has been done into the sensor package that is applicable for the AIRTuB project to carry out autonomous inspections of wind turbine blades offshore. A literature study has been performed into the damage and failure modes that occur to wind turbine blades, distinguishing between damage that occurs on the outside of the blade, such as leading edge erosion (LEE), and damage that occurs below the surface, on the inside of the blade, such as delamination of the composite materials. Based on this overview, a list has been produced of sensor systems that qualify for this application within the methodology of the AIRTuB autonomous inspection project. Research has been done on both lab scale and demonstration scale on both cut-off samples from a decommissioned wind turbine blade with artificial and in-service damages. The results form input for the other work packages in for design requirements and blade damage inspection data processing.

Objective/goal

The general goal of the WP1 is to design concept non-destructive sensor(s) which is/are capable of detecting relevant damages on the wind turbine blade under the off-shore condition and which can be carried by an unmanned system aiming for automated remote inspection.

The sub goals:

- Develop sensor packages suitable to perform internal and external inspections that can be carried by AIRTuB drone and crawler
- An overview and characterization of failure modes which occur on wind turbine blades with detection and inspection limits relevant for O&M strategies
- An overview of applicable sensor methods and technologies which can be applied for the autonomous inspection of wind turbine blades
- Demonstration and testing of sensor systems to detect both damages on the outer surface and internal the blade

Way of working

The work package is divided into five different subtasks which are performed by all partners in the WP 1:

- WP 1.1 Study on blade erosion, internal damage and use cases (TNO, NLR)
- WP 1.2 Design of external blade damage inspection sensor (TNO, NLR, TU Delft)
- WP 1.3 Investigation of working principles external damage inspection (TNO, NLR, TU Delft)
- WP 1.4 Comparison study internal damage inspection (NLR, TU Delft, Dutch Terahertz)
- WP 1.5 Investigation of working principles internal damage inspection (NLR, TU Delft, Dutch Terahertz, HZ Robotics, Hanze)

Working procedure

<u>WP 1.1 Study on blade erosion, internal damage and use cases (TNO, NLR, TU Delft, Hanze)</u>

A study has been performed based on literature with the state-of-the-art knowledge of damage types to wind turbine blades to deliver the design criteria and requirements for the sensors to be developed for offshore blade inspection. The study is divided into internal defects in the blade such as delamination and external damage such as due to water droplet impact erosion on the leading edge (LEE). Based on the results the use cases are determined and which inspection methods will be viable in the remaining WP.

Deliverable:

- Final report literature review of structural and non-structural wind turbine blade damage, Rogier Nijssen, Emilio Manrique, TNO 2020 R10402, 10 Sept 2020

Based on the study a distinction is made between structural and non-structural damage. In the latter case the main focus is on LEE, which is typically encountered in the blade tip area. For this damage type, a classification system is discussed. Blade structural damage in the field indicate manufacturing or design defects and, often, damage to blade root connections (bolts).
Secondary damage due to lightning strike are combined in any statistics that are available. Mechanical tests on blades or blade parts carried out in the laboratory are best-documented, but under less realistic conditions than in the field.
The general outcome of the study is an overview of realistic minimum detectable damage sizes for both structural and non-structural damage given in Table 1 which is used as criteria for the other tasks.

Table 1. Minimum detectable damages.

Type	Location	Minimum detectable depth [mm]	Minimum detectable diameter [mm]	Motivation
Leading edge erosion	20-30% outboard, leading edge. Superficial	0.3	2	Critical
Lightning	Near receptors (blade tip and mid-airfoil, pressure and suction side, black spots)	0	15	Typical lightning damage, repairable
Structural (gelcoat cracks indicating deeper damage)	Trailing edge	0	Hairline, 100mm length	Larger than Quality Assurance
Structural (delamination in root laminate)	20% inboard	75	100	Larger than Quality Assurance
Structural (delamination in outer skin-core bond of sandwich)	60% inboard, sandwich panels between spar caps and leading/trailing edge	2 - 5	100	Larger than sandwich block grid size
Structural (bondline tunneling or disbond cracks)	Web-spar cap, leading/trailing edge	0 - 30	Hairline (tunneling) or 25 (disbond)	Larger than Quality Assurance

WP 1.2 Design of external blade damage inspection sensor (TNO, NLR, TU Delft, DfW, HZ Robotics, Hanze)

A literature study has been conducted focusing on the modern Non-Destructive Inspection (NDI) methods that have potential to be carried and operated by unmanned vehicles. Based on the type of damage characterisation and evaluation like LEE, 3D imaging solution can provide that information such as photogrammetry, structured light and multispectral imaging, the triangulation based laser 3D shape sensing seems the best suitable method. This conclusion is made based on the fact that this method is less dependent on the visually recognizable features on the wind blades to stitch the data together. Table 2 provides the key results from this literature study.

Table 2. Strength and weakness of 3D scan methods

Scan method	Strength / Features	Weakness
Passive methods (Photogrammetry)	• Distance of measurement between 0.1 to few meters • Accuracy depends strongly on the distance to the object • Miniaturization is easy to achieve, light weight components are commercially available	• Surface with sufficient visual characterizations are required • Erosion depth is hard to determine
Structured light	• Distance of measurement varies from 0.1 to several meters • Accuracy from 10 µm	• Strongly dependent on the light condition • Sensitive to vibration • Surface with sufficient visual characterizations are required
Triangulation laser	• Distance of measurement varies from order of 0.01 to 1 m • Accuracy from 10 µm • Available in many forms: (multi) line/area scanner, handheld scanner, portable arm • Less sensitive to ambient light	• Sensitive to the surface condition
Phase shift laser	• Distance of measurement varies from order of 1 to 100 meter • Accuracy from 2 mm • Less noisy compared to other laser techniques	• Accuracy is insufficient to detect damage • Large distance to the object is needed • No miniaturized system available
Time of flight laser (LIDAR)	• Distance of measurement varies from order of 1 to 100 meter • Commercial system is available for drone platforms (LIDAR)	• Accuracy is insufficient to detect damage
Spectral imaging	• Distance of measurement from 1 m	• Surface damage assessment (depth) is not possible • No robust system available for drone application

In this WP, the first laser line scan based sensor demonstrator is developed. This takes into account the interfaces with the applied drones to be developed in WP2. Detailed blade inspection sensor design is developed for the applicable sensor systems. Including selection of sensors for external offshore blade inspection concerning the mechanics, optics, power supply, mounting on the drone, etc.

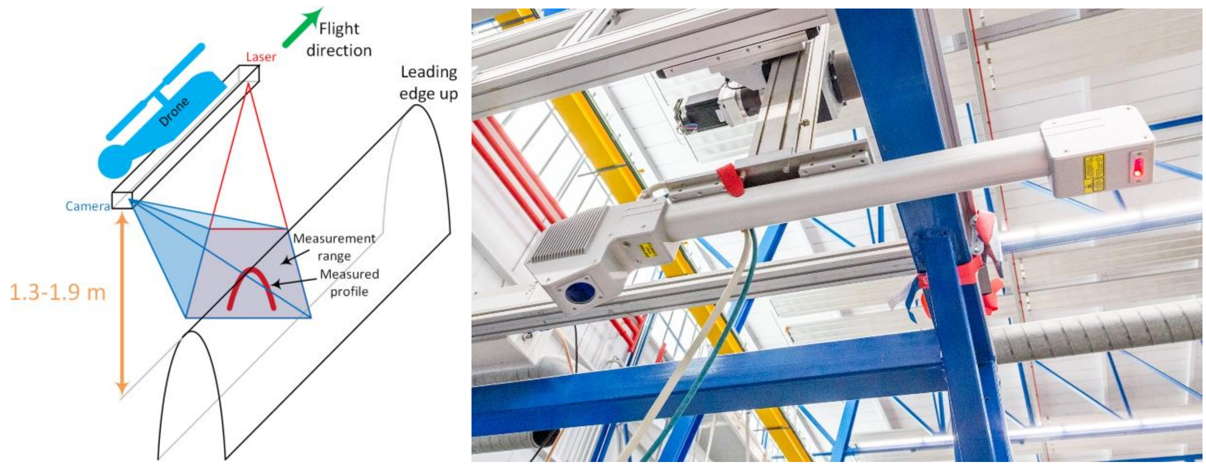


Figure 1. Laser line scan concept, tested on the reference specimen.

Deliverable:

- A Literature Survey on Remote Inspection of Offshore Wind Turbine Blades, Automated Inspection and Repair of Turbine Blades (AIRTuB) - WP1, J.S. Hwang, D.J. Platenkamp, R.P. Beukema, NLR-CR-2020-223, May 2021
- Off-Shore Wind Turbine Blade Erosion Inspection Sensors using an Unmanned Vehicles – WP1, J.S. Hwang, R. Beukema, A. Anisimov, NLR-CR-2021-248 (DRAFT)
- Anisimov, A. G., Beukema, R., Hwang, J., Nijssen, R., & Groves, R. M. (2021, June). AIRTuB: towards automated inspection of leading edge erosion of wind turbine blades by shape analysis. In *Multimodal Sensing and Artificial Intelligence: Technologies and Applications II* (Vol. 11785, p. 117850W). SPIE.

<u>WP 1.3 Investigation of working principles external damage inspection (TNO, NLR, TU Delft, Inholland, Dutch Terahertz)</u>

Within this work package, a demonstration environment has been created for lab-scale testing of sensor systems on fabricated composite test samples with standardised damage profiles (depth, size) and sections of damaged blades. The sensors for external inspection of the blades are based on optical detection systems and have been developed within the project with the necessary data processing and systems for mounting to a drone (interface, power supply, etc). Based on the tests, the experimental data was evaluated and the sensor systems were further improved. Figure 2 shows some highlights from this WP.

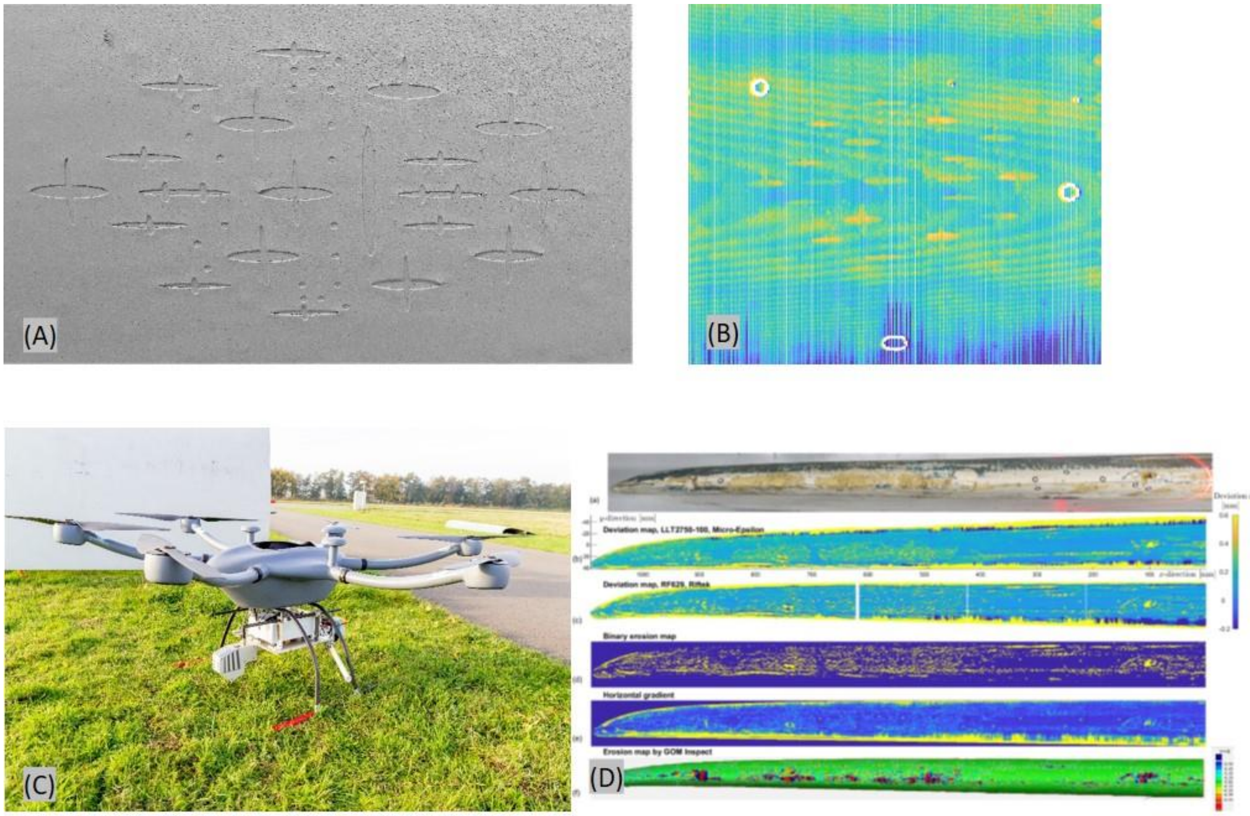


Figure 2. (A) shows the artificial erosion pattern attached to the leading edge. (B) shows the results of the laser line scan from (A). On the final demonstration day, the sensor was carried underneath the drone and performed inspection flight. (D) shows various algorithm developments.

Deliverable:

- Off-Shore Wind Turbine Blade Erosion Inspection Sensors using an Unmanned Vehicles – WP1, J.S. Hwang, R. Beukema, A. Anisimov, NLR-CR-2021-248 (DRAFT)
- In-flight tested prototype of the sensor package for the numerical characterisation of the leading edge erosion based on the laser-line triangulation sensor, acquisition unit and processing algorithms
- Anisimov, A. G., Beukema, R., Hwang, J., Nijssen, R., & Groves, R. M. (2021, June). AIRTuB: towards automated inspection of leading edge erosion of wind turbine blades by shape analysis. In *Multimodal Sensing and Artificial Intelligence: Technologies and Applications II* (Vol. 11785, p. 117850W). SPIE.

<u>WP 1.4 Comparison study internal damage inspection (NLR, TU Delft, Dutch Terahertz)</u>
Within this task, the sensor methods for internal damage inspection have been selected based on internal blade damage failure modes like delamination of the composite material. The sensors have been tested on a lab scale where the measurement data has been analysed and implemented to improve the sensor systems for this specific application.

For detecting internal structural damage modes in a wind turbine blade like adhesive joint failure between skins and sandwich panel face/core debonding, the ultrasonic-based NDI methods is found to be most suitable because of its miniaturization possibility, manoeuvrability and damage detection capability for thick composite material. Phased array ultrasonic inspection method, especially in the form of array integrated in a wheel, may provide practical solution. Wheel probe can cover large area in a rolling motion, suitable to a large area of wind turbine blade. Furthermore, there are many developments in the field of data processing and presenting from the phased array inspection, such as full matrix capture and total focusing methods, which can be added value to take into account in the further developments in the AIRTuB project.

In this WP, numerous reference specimens with artificial defects are prepared and distributed among the partners. These reference panels serve as baseline for different NDI techniques to be compared to each other. Baseline C-scan is performed as well as 3D imaging to establish exact geometry of the part. Furthermore, microscopy images are made to understand the composition and the quality of the material.

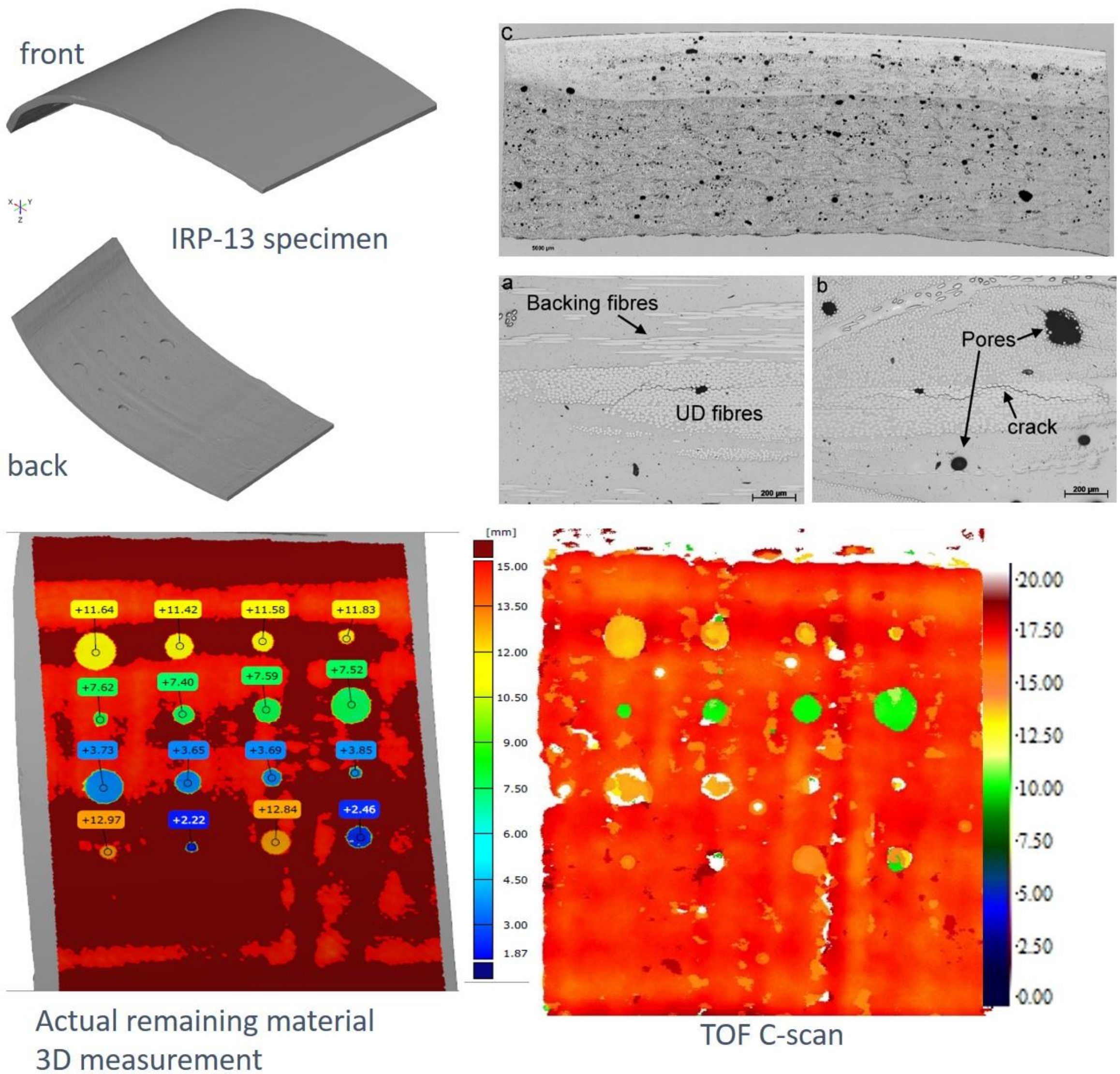


Figure 3.

Deliverable:

- A Literature Survey on Remote Inspection of Offshore Wind Turbine Blades, Automated Inspection and Repair of Turbine Blades (AIRTuB) - WP1, J.S. Hwang, D.J. Platenkamp, R.P. Beukema, NLR-CR-2020-223, May 2021

<u>WP 1.5 Investigation of working principles internal damage inspection (NLR, TU Delft, Dutch Terahertz)</u>
Within task 1.5 a demonstration environment has been created in which the selected sensor systems are tested on sections of used wind turbine blades with damages. The sensor methods used is ultrasonic

inspection for damage directly below the surface in the composite material. For this application, a drone is used that transports a crawler to the blade that can move over the surface with the sensor (Figure 4).

During the development of the first version of the sensor package, it was concluded that the further miniaturization and light-weight design is necessary. Therefore, the next generation sensor has been conceptualized with new sensor design, communication method and lighter data acquisition system. The new sensor has been validated on the reference specimen. See Figure 5 for this concept.

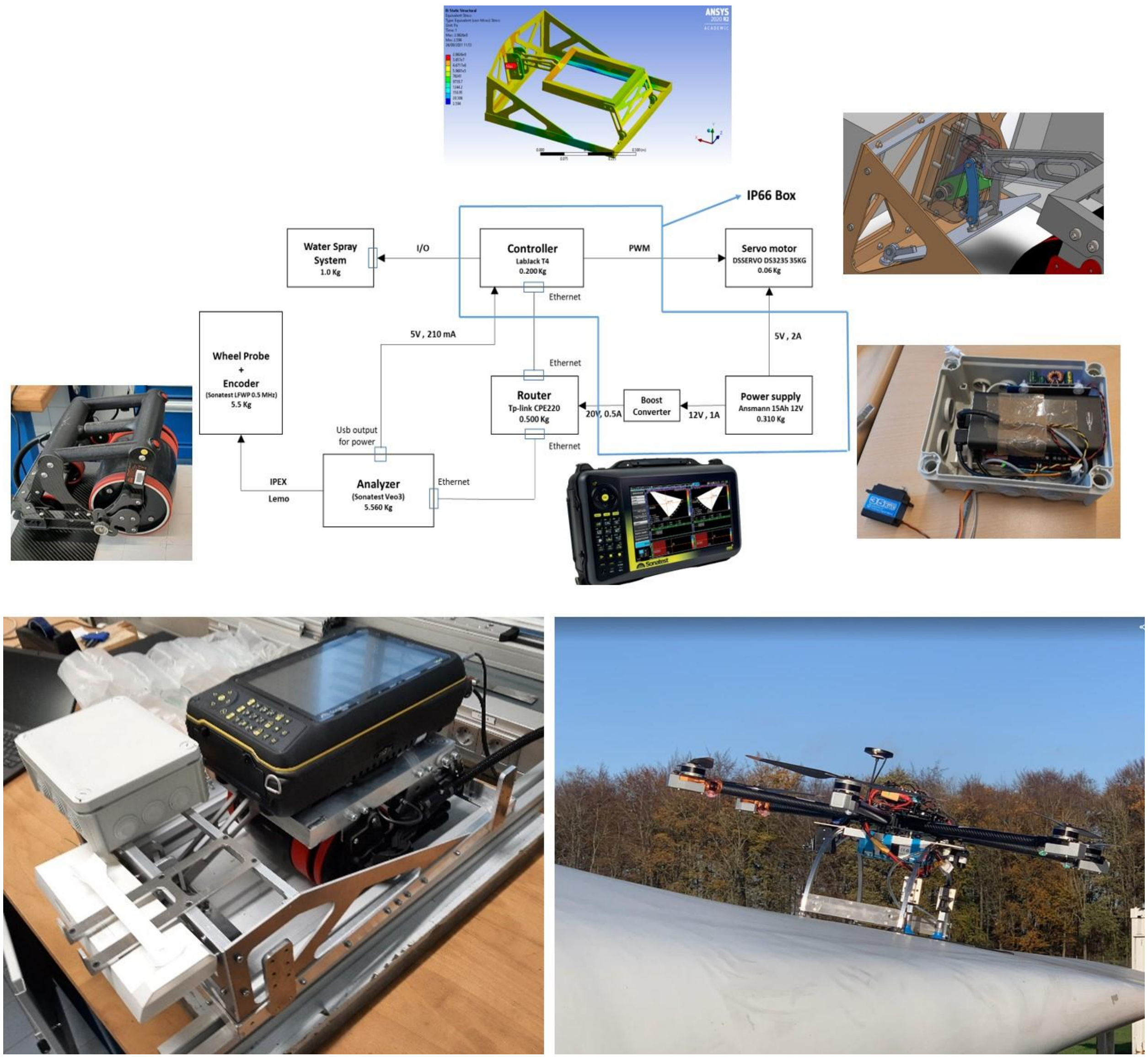


Figure 4 Development and demonstration of the ultrasonic sensing package that could be carried by a crawler. On the demonstration day, the crawler landed on top of the wind turbine blade with help of the drone.

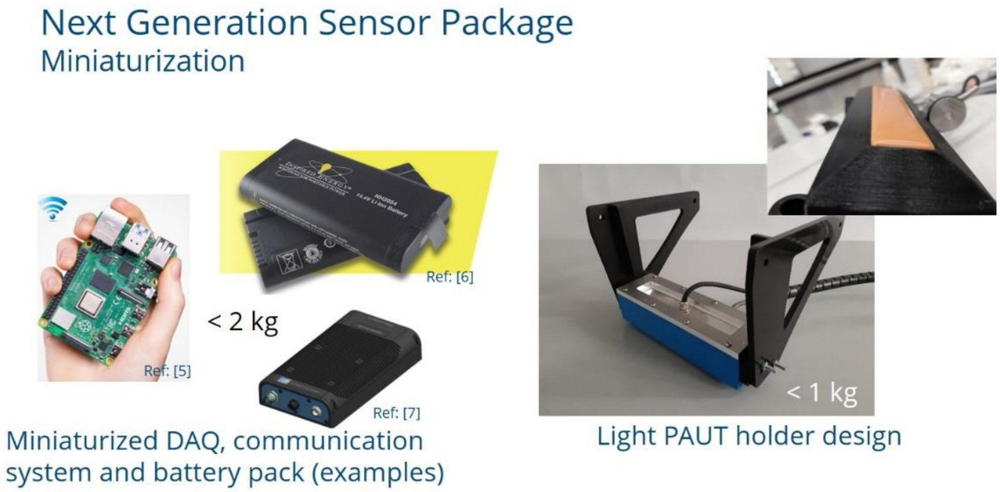


Figure 5. Next-generation sensor package aims to further miniaturize to achieve light payload in favor of operational time and flexibility.

Deliverable:

- Remote Ultrasonic Inspection of Offshore Wind Turbine Blades, D.J. Platenkamp, V.S.V. Dhanisetty, A. Chabok, A.F. Bosch, NLR-CR-2021-177, (DRAFT)
- A lab-prototype sensor package which has the potential (size, weight, energy) to be further developed into a prototype sensor module to be transported by a drone, and which is able to determine the surface contour of an operational wind turbine blade and extract damage information, such as LEE, on the outer surface. (NLR)
- Cheng, L., Nokhbatolfoghahai, A., Groves, R. M., & Veljkovic, M. (2022, June). Acoustic Emission-Based Detection in Restricted-Access Areas Using Multiple PZT Disc Sensors. In *European Workshop on Structural Health Monitoring: EWSHM 2022-Volume 1* (pp. 619-629). Cham: Springer International Publishing.
- Cheng, L., Nokhbatolfoghahai, A., Groves, R.M. and Veljkovic, M 2023. "Using Deep Learning for multi-sensor data fusion of signals from commercial acoustic emission and piezoelectric disc sensors". Structural Control and Health Monitoring, Under review.

Conclusion and recommendations

The main conclusions and outcomes of the WP1 are

- The relevant failure modes and detection limits for blade inspection are evaluated based on a literature study.
- Sensor systems applicable for the external blade damage detection are based on optical and laser scanning (3D) technology to characterize and quantify the damage surface damages (LEE, etc)
- The leading edge erosion with depth variations from 0.2 mm and higher (deeper) can be detected with the developed sensor package mounted on a drone in real flight tests, including the laser line scanner.
- Ultrasonic detection technology is applicable for subsurface/internal damage detection in the blade like detection of delamination in the shell.
- The internal blade inspection method based on ultrasonic technique is mounted on a crawler system which can be attached on and transported over the blade surface with a suction cup system.
- All selected sensor methods are tested on both lab scale and demonstration scale to produce the required information for the inspection and maintenance of the blades.

<u>Recommendations</u>

Both laser line scan method for external erosion and ultrasonic inspection for internal delamination have proved to be feasible. The laser line scanner requires the drone to be flying stable with constant speed along the pre-fixed path and distance from the leading edge. Good drone controller is essential for the accuracy of the measurement. Ultrasonic sensor package needs to be much lighter to enable longer operational range of the crawler and drone. The next generation sensor design can help to reduce weight of the total package.

- Availability of relevant wind turbine blade specimen is essential. In this project, the reference standard was from a 30+ year old blade. Over the time, the manufacturing techniques would have been evolved, which could have both positive and negative effect on the defect detectability of the concepts developed in this program. Unfortunately, this most current specimen was not available, therefore, it is still uncertain if this approach is viable for our target wind turbine blades.

Figure 6 Further development of the sensor packages suitable to perform internal and external inspections that can be carried by AIRTuB drone and crawler