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Final report AIRTuB (Automated Inspection & Repair of TurbineBlades)

(TEHE119002)

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“Het project is uitgevoerd met subsidie van het Ministerie van Economische Zaken en Klimaat en het Ministerie van Landbouw, Natuur en Voedselkwaliteit, Nationale regelingen EZK- en LNV-subsidies, Topsector Energie uitgevoerd door Rijksdienst voor Ondernemend Nederland.”

Project information

- Projectnumber: TEHE190002
- Project title: Zephyros AIRTuB
- Project administrator: Worls Class Maintenance
- Participants: Eneco, Stork, Demcon, Qlayers, Fusion Engineering, LM Windpower, DutchTerraHertz, TNO, NLR, TU-Delft, Hanze Hogeschool, Inholland, HZ-UAS, Scalda*, Saxion Hogeschool**, DCMC**
- Project period: 01-09-2019 – 17-02-2023

* subcontractor of HZ-UAS

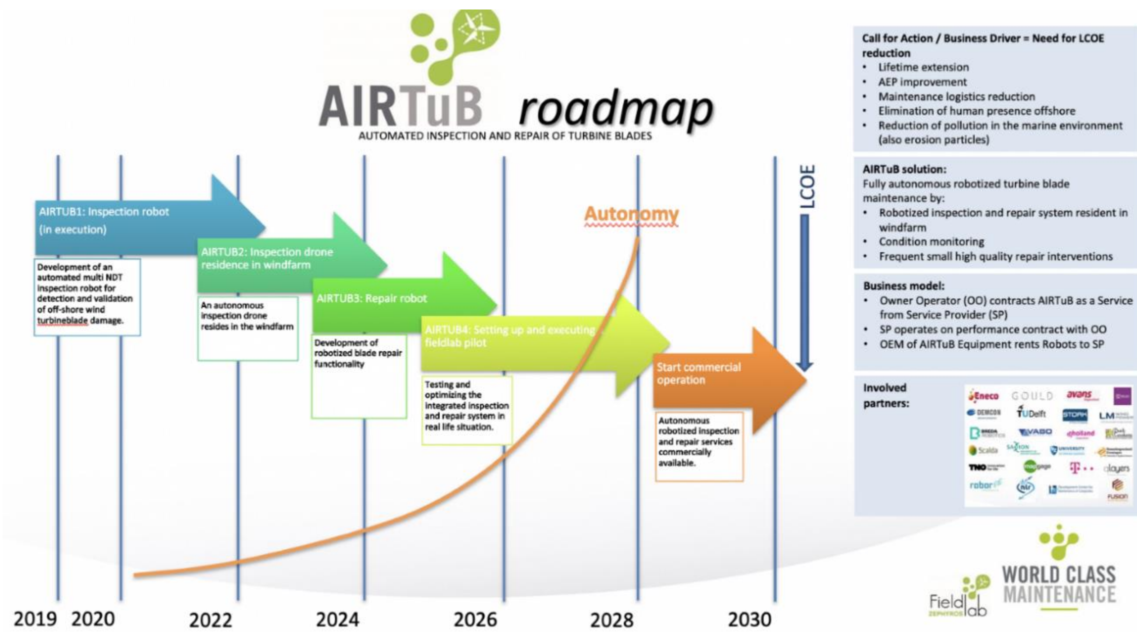
** dissemination partner

Contents

0. Public summary

The AIRTuB (Automated Inspection and Repair for offshore windTurbine Blades) program consists of multiple R&D projects that aim to develop automated and smart-maintenance solutions for the maintenance of offshore windturbine blades.

Figure 1. AIRTUB program roadmap for developing unmanned solutions for blade inspection and repair.



In this first AIRTuB project, firstly, wind turbine blade damage was researched, and inspection technologies (sensors) were investigated. Secondly, prototypes and an innovative flight controller were developed to deploy those sensors from a drone and a crawler that could be landed on a windturbine blade. These prototypes have successfully been demonstrated in a controlled environment. In addition, robotized coating technology was successfully developed for (future) automated blade repair. Also, in order to better understand the effects of Leading Edge Erosion (LEE), models for the prediction of AEP losses from blade erosion were developed and validated and machine learning was used to classify erosion types. And, finally, business cases for automated blade repair were developed so they can be used for future asset management strategies.

Despite some setbacks and delays during the project, resulting in a scope change, the deliverables have been achieved and the project has resulted in the following innovations:

Development and demonstration of:

- an innovative flight controller by Fusion engineering
- a prototype laserline scanner for measuring LEE
- a large drone (40+kg) for carrying to and landing a crawler with sensor on a windturbine blade
- a crawler with ultrasonic sensor to measure internal damage inside blades
- algorithms to process the data from laserline scanner and ultrasonic sensor
- a printhead for robotized precision coating of windturbine blades
- machine learning to classify erosion types

Publication of:

- Validation of models for the prediction of AEP losses from leading edge erosion
- Various scientific papers
- Various articles, video clips, lectures etc, about automated blade inspection and repair.

Conclusions

While automated inspection and repair of off-shore wind turbine blades is still very challenging from a technical and regulatory perspective, the results from the AIRTuB project are promising and show that there clearly is potential for significant optimisations of asset management strategies and associated AEP improvement and O&M cost savings.

- Validated wind tunnel tests showed that leading edge erosion has a significant impact on AEP upto 1,24%, depending on the erosion level.
- The project also showed that high precision robotized coating of blades is possible and can potentially help reduce AEP losses:
    - After coating the 3 wind tunnel sections from LM, the results showed that the loss of aerodynamic performance caused by the LEP is partially regained by adding a chamfer. Based on the wind tunnel measurements for a typical modern offshore wind turbine, there is a reduction of 0.42% in Levelized Cost of Energy (LCoE)[1] caused by the post-applied LEP towards additional chamfering. The theoretical maximum achievable LCoE reduction of this technology is 1.16%.
- Modelling by Stork and HZUAS with data from Eneco show that significant O&M cost savings (upto 80%, compared to rope access) are possible with automated inspections and repairs with drones and crawlers, compared to the baseline (traditional rope access), these cost savings remain substantial even if rope access inspection is replaced by visual (camera) drone inspections.
- 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.

- The laser scanner data can be used for storing size and position of blade damages. Therefore data is usable for automatic classification of blade damage.
- Ultrasonic detection technology is applicable for subsurface/internal damage detection in the blade like detection of delamination in the shell.

Recommendations

- Miniaturisation of drone and crawler, and drone residency in the windfarm, are needed for 'unmanned' solutions to reach full cost saving potential.
- Regulatory reform is urgently needed to make autonomous robotized inspection/repair a reality, with a human in a control room ashore .
- Frequent maintenance with high accuracy robotized printing as repair of LEE needs to be studied as a way to keep blades in optimal shape, increase blade life and increase AEP.
- Increased monitoring to better identify the 'region of interest', where structural damage inside the blade might occur, and more attention of lightning damage, is needed.

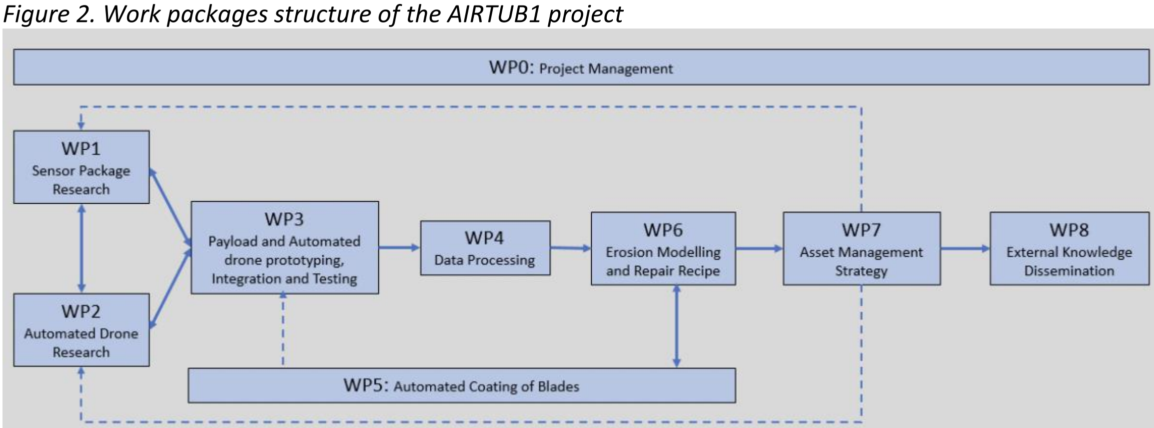
1. Introduction

Off -shore wind energy in The Netherlands is almost 20 years old now. Numerous wind parks have been constructed further out at sea, with ever bigger turbines, longer travelling times, more operational hours and taller blades to inspect. With the limited human resources that are available in Western Europe, the situation of too many turbines, too large and too far away to manually maintain, is rapidly approaching.

Unmanned blade maintenance with drones and robots has the potential to increase annual energy production (AEP), reduce maintenance-related logistical operations at sea, reduce maintenance cost and address a future manpower shortage.

The AIRTUB 1 project (2019-2023) was the first in a series of projects that together make up the AIRTUB program which aims at the development of technologies for unmanned maintenance in off-shore wind energy. The project focussed on investigating the nature of blade damage and the technology to detect such damage (workpackage 1), developing a drone and a crawler to inspect such damage (WP2 and 3), collect and process data from monitoring and inspections (WP4), develop and demonstrate robotized blade repair with high accuracy coating (WP5), to establish a link between Leading Edge Erosion (LEE) and loss of Annual Energy Production (AEP) by means of windtunnel validated models (WP6) and to develop a future asset management strategy for windturbineblades.

Figure 2. Work packages structure of the AIRTUB1 project

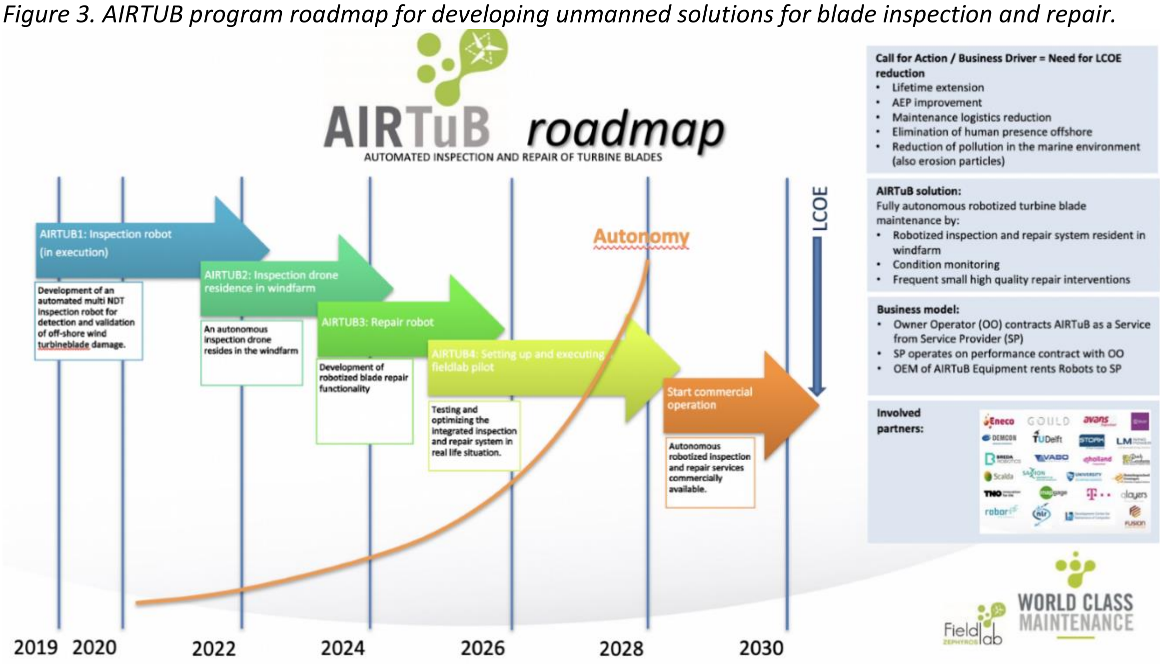


The project (including initiating and proposal preparation phase) was a four-year collaboration between research institutes and private companies aimed at identifying various types of blade damage, working towards developing autonomous drone and crawler technology for blade inspections, establishing the relationship between leading edge erosion (LEE) and loss in Annual Energy Production (AEP), and developing a robotized system for accurate blade coating.

The AIRTUB1 consortium consisted of research institutes (TUD, NLR, HZUAS, InHolland, TNO, Hanze Hogeschool) and private companies (Demcon, Fusion Engineering, LM windpower, Qlayers, Eneco, Stork and Dutch Terrahertz).

On November 24, 2022, the consortium succesfully demostrated in-flight leading edge scanning with a laserline scanner mounted on a drone, ultrasonic scanning of a blade, with a sensor that was mounted on a crawler that could be delivered to the blade with a large drone, and a drone flight with a special 'gust proof' flight controller with a non-linear control mechanism.

Figure 3. AIRTUB program roadmap for developing unmanned solutions for blade inspection and repair.



2. Windturbine blade damage research (WP1)

Desk research by the consortium partners in WP1 (TNO, TUD, Inholland, Dutch Terrahertz, LM windpower, Eneco) resulted in the following overview of types of blade damage, refer to Table 1:

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

2.1 Leading Edge Erosion blade scanning technologies

Based on the previously described types of blade damage, various scanning technologies were assessed for their suitability, refer to Table 2.

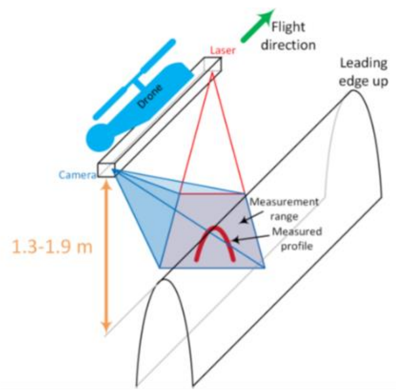
Table 2. Strength and weakness of 3D scan methods

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

2.2 LaserLine scanner for Leading Edge inspections

As a result of desk research of the technologies, and after careful evaluation, a LaserLine scanner (LLS) was developed by TUD and used in combination with a drone to fly close to the leading edge and inspect the leading edge for erosion, see Figure 2.

Figure 4. Laser Line scanning technology: working principle (left) and prototype mounted under a drone (right).

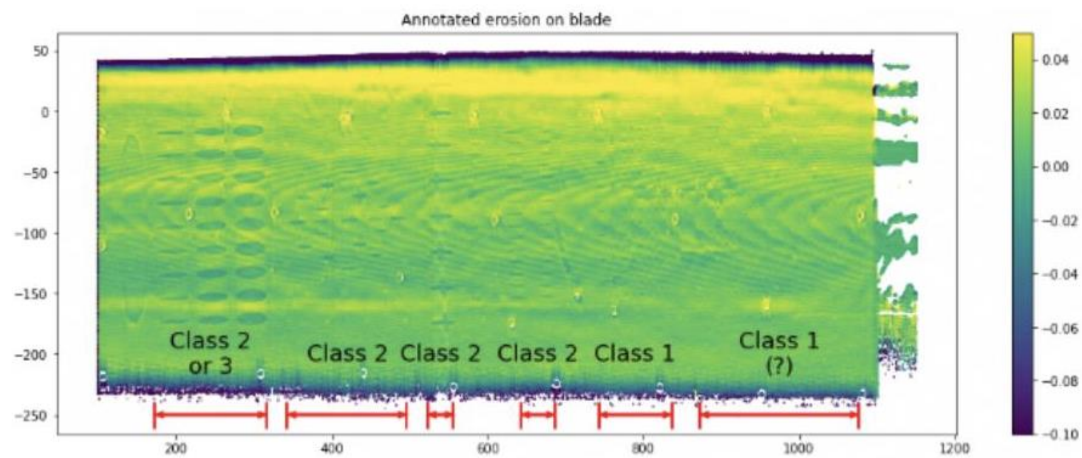


The results from this scanner showed that it is possible to use it for measurement of LEE in a fly-by mode with a drone at less than 2m from the LE.

2.3 Development of machine learning algorithms

Subsequently, the project demonstrated automatic categorization of LEE damage with the help of specially developed machine learning algorithms, see Figure 3.

Figure 5. Laser line scan with erosion on the leading edge of a wind turbine blade (top), automatically classified with machine learning (bottom).



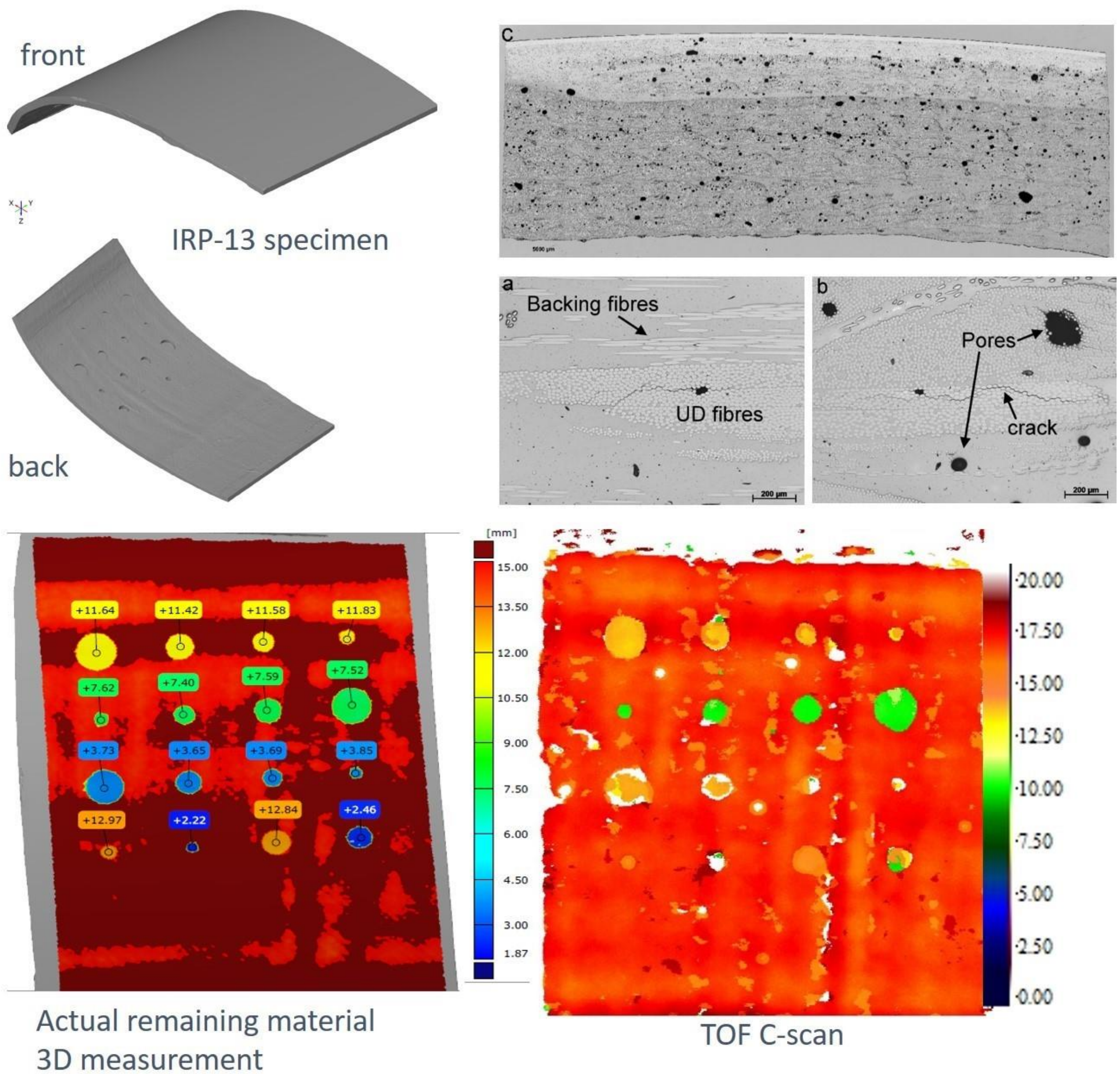
The focus was on machine learning to predict LE erosion classes. Machine learning methods need a known output, also called a target (in this case the erosion class) and corresponding variable data, also called features. The starting point for collecting such data was a definition of erosion classes.

There are five classes, and membership of a class is defined by area (mm) and depth (mm) of the erosion. Since depth has to be measured, a specific sensor needed to be selected to generate feature data. To that end a 3D laser line scanner was used. For prototyping the method a suitable LE part of 1m length was provided. After scanning this part, the resulting image was divided in slices. Each slice was labeled manually with a the known erosion class. Then the resulting data set was split into a train and a test set. Training data was used to create the prediction model. For this purpose several machine learning methods were compared. The best performing model was used on the test set, which resulted in an accuracy of almost 65%. This looks very promising, but the dataset that was used was very small, and only held examples of erosion classes 1 and 2. Hence, the selected method and procedures proved to add value, but need to validated with more data, coming from several blades in several “health” states.

2.4 Ultrasonic Sensor scans for identification and assessment of Internal damage

For the detection of internal damages, after extensive testing by TUD and NLR, a phased array ultrasonic sensor was selected for inspection of the internal damage inside the wind turbine blade.

Figure 6. Ultrasonic scan results of damages on a windturbine blade.



3. Development of a drone and a crawler for blade inspections WP 2 & 3

In order to deploy the laserline scanner and the ultrasonic sensor, a drone with sufficient capacity (total take off weight of 40+ kg) was developed, see Figure 5. In addition to the drone, a crawler was developed by HZ-UAS. This crawler could be landed on the wind turbine blade by the drone and hold the ultrasonic sensor so it could take measurements. In order to stick to the blade, the crawler is equipped with a suction cups system.

Finally, a special flight controller has been developed by Fusion engineering. This flight controller has a non-linear control algorithm, allowing it to fly with a heavy drone very close to a wind turbine blade in gusty conditions.

Figure 7. Drone with crawler flying at NLR during the demonstration on November 24, 2022.

4. Data processing and development of asset management strategy (WP4 and WP7)

Based on data from Eneco (esp the prinses Amalia windfarm), Eneco, Stork and HZUAS have worked to develop scenarios for O&M cost, comparing baseline 1 (rope access for inspection and repair) and a later baseline 2 (partial drone visual inspections with a drone flown from a vessel, or from a hub (docking station), where the drone is resident in the windfarm.

Table 3: Cost savings potential autonomous drone inspection and repair of wind turbine blades.

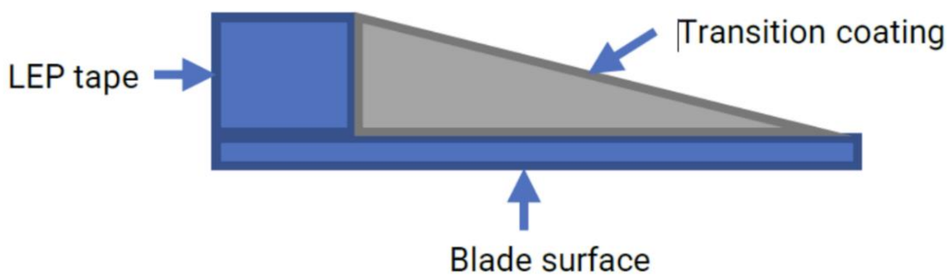
		Baseline 1	Baseline 2	Scenario 1a	Scenario 1b	Scenario 2	Scenario 3
SPECIFICATIONS	Inspection	Rope access	4-K Camera	4-K Camera + Laserscanner+ Crawler ultrasonic	4-K Camera + Laserscanner+ Crawler ultrasonic	Autonome inspection with 4-K Camera + Laserscanner+ Crawler ultrasonic	inspection with 4-K Camera + Laserscanner+ Crawler ultrasonic
	Drones		Small Drone	Large Drone	Large Drone	HUB	small drone for Laserscanner
				Large drone for crawler	Large drone for crawler	HUB	Large drone for crawler
	Repair	Rope access during inspection (cat 1 and 2)	Rope access (separate)	Rope access (seperate)	Crawler during inspection (cat 1 and 2)	Crawler (cat 1 and 2)	Crawler (cat 1 and 2)
		Campaign > cat 2	Campaign > cat 2	Campaign > cat 2	Campaign > Cat 2	Campaign > Cat 2	Campaign > cat 2
Benefitial comparison with baseline:				Better classification Less repair time Learning curve Remaining life indication	Better classification Learning curve Much less logistic cost Remaining life indication Quick automated repairs by crawler (CAT 1, 2)	Better classification Big learning curve Very little logistic cost Remaining life indication Quick automated repairs by crawler (CAT 1, 2)	Better classification Big learning curve Very little logistic cost Remaining life indication Quick automated repairs by crawler (CAT 1, 2)
Points of attention:				Repairs still with rope access or campaigns Logistic cost less but still high	Additional and sophisticated specification for crawler	Investment for HUB Investment for controller (autonomous) Investment for crawler	Additional and sophisticated specification for crawler

- Potential windturbine blade maintenance cost savings with autonomous drone/crawler inspection and repair over the wind turbine lifetime has been estimated at 30-60%: these are savings to maintenance cost compared to baseline 1 (conventional rope-access, case of the Amalia windfarm).
- Compared to baseline 2 (visual inspection by drone from a vessel, combined with rope access for repairs) this savings potential drops to 10-30%.
- The savings are caused by a shorter duration and higher frequency of inspections resulting in a steeper learning curve, which in turn is leading to quicker, better and more timely repairs, resulting to better overall asset management: 10-50% O&M cost reduction, compared to baseline 1.
- High quality scans with laserscanner lead to better learning curve and lower logistical cost if a smaller drone is used for the laserline scans while a bigger drone is used for the crawler/internal damage inspections are estimated to bring 10-40% cost reduction in scenario 3.
- With drone/crawler residency in the windfarm, increased learning curve effects can be achieved leading to estimated potential blade O&M savings of 40-80% compared to the baseline 1 (traditional rope access) and 10-30% savings compared to baseline 2.
- Additional effects such as potential postponement of the end of blade life, have not been quantified.

5. Development of a robotized print head for coating wind turbine blades (WP5)

Specialized robotized coating company Qlayers developed a robot-print head to apply a very thin coating on a windturbine blade. This type of coating technology may be used for the in-situ repair of damage on windturbine blades in the future but in this project, it was used to ‘fill’ the transition between leading edge protection (LEP) tape and the blade surface itself (see Figure 6). The filling of such a transition reduces turbulence and improves the aerodynamic performance of the blade.

Figure 8. Schematic representation of the transition from Leading edge protection (LEP) tape to blade surface, with transition coating from Qlayers.



Subsequently, Qlayers used the newly developed printhead to print the transition on an LM wind turbine blade which equipped with a leading edge protection (LEP) and it was tested in a wind tunnel. The results of the wind tunnel measurements show that the reduction in LCoE from a post-applied LEP towards an additional chamfering is in the order of 0.42% for a typical modern offshore wind turbine. The maximum achievable LCoE reduction would equal nullifying the LEP impact which would be 1.16%.

6. Development of (validated) models for the prediction of AEP losses from blade erosion (WP6)

With the prediction of the aerodynamic AEP losses from blade erosion, the challenge lies in a good prediction of 2D lift and drag coefficients of eroded airfoils. The established methods of computational fluid dynamics (CFD) and flow engineering were developed, improved and validated with wind tunnel measurements of eroded airfoils. The comparison generally showed a good agreement. Moreover a blade has been scanned and the scanned geometry is used as input to a CFD method. AEP losses from this procedure ranged between 0.86% and 1.24% dependent on the erosion level.

7. Project management and Dissemination (WP0 and 8)

Project management and technical project coordination was performed by WCM by means of appointing a dedicated project manager and a technical project coordinator.

At the start of the project the collaboration agreement (also arranging IPR management) was signed by all partners, a shared data drive was facilitated for sharing and storing project data by all project partners and a bi-monthly WPlead meeting schedule and a semi-annual steergroep meeting schedule was established and operationalized during project execution. Special attention was given to managing scope, planning and interface bottlenecks.

Dissemination was coordinated and facilitated by WCM. At the start of the project it was agreed to organize an annual AIRTuB event in collaboration with the aligning projects MARS4EARTH (Saxion UAS) and FIXAR (InHolland UAS). Also a general AIRTuB roll-up banner and some artist impressions of aimed for AIRTuB deliverables were developed and delivered to all project partners to expose where AIRTuB activities would take place. During the last year of the project specific AIRTuB Workpackage events were organized to share results with the market. The closure event at the NLR premises showed and demonstrated all final results of the project. All generated exposure resulted in the situation that one could say that AIRTuB is now a household name related to wind turbine blade maintenance.

Besides the AIRTuB project has been presented during numerous events and occasions as listed in the dissemination report. The Knowledge institutes have issued a long list of reports on the findings of their research in the AIRTuB project.

Figure 9: AIRTUB team and public after the succesfull demonstration on November 24, 2022 at NLR in Marknesse, with various drones and crawler (on the wind turbine blade).

7.1 Bottlenecks and problems encountered during the project.

The project successfully achieved many of its objectives, resulting in the development and demonstration of an advanced flight controller, a prototype drone and crawler for ultrasonic inspections inside a wind turbine blade, a laserline scanner for measuring LEE, and a printhead for accurate blade coating and it modelled the relation between LEE and AEP, which subsequently were validated in wind tunnel tests. These advancements have the potential to significantly improve the efficiency and safety of wind turbine maintenance, ultimately leading to increased renewable energy production.

- Office and laboratory development and experimentation work was severely affected by the COVID19 pandemic. The scientists working on the project have tried their best to carry on as good as possible despite various restrictions imposed by the government or individual organisations.
- Development of the Reflex flight controller by Fusion Engineering was more complex and costly than expected and therefore took much longer than planned. As a result , a scope change was requested and granted and the project ended with a demonstration in a controlled environment at NLR and the field test and subsequent data collection from the field were not carried out.
- Various regulatory, health and safety and insurance issues with regards to field tests and data collection with inspection drone and crawler on real operational windturbines were underestimated at the start of the project.

8. Conclusions and recommendations from the AIRTUB1 project

8.1 Conclusions:

While automated inspection and repair of offshore wind turbine blades is still very challenging from a technical and regulatory perspective, the results from the AIRTuB project are promising and show that there clearly is potential for significant optimizations of asset management strategies and associated cost savings.

- Validated wind tunnel tests showed that leading edge erosion has a significant impact on AEP upto 1,24%, depending on the erosion level
- The project also showed that high precision robotized coating of blades is possible and can potentially help reduce AEP losses:
  - After coating the 3 wind tunnel sections from LM, the results showed that the loss of aerodynamic performance caused by the LEP is partially regained by adding a chamfer. Based on the wind tunnel measurements for a typical modern offshore wind turbine, there is a reduction of 0.42% in Levelized Cost of Energy (LCoE)[1] caused by the post-applied LEP towards additional chamfering. The theoretical maximum achievable LCoE reduction of this technology is 1.16%.
- Modelling by Stork and HZUAS with data from Eneco show that significant O&M cost savings (upto 80%, compared to rope access) are possible with automated inspections and repairs with drones and crawlers, compared to the baseline (traditional rope access), these cost savings remain substantial even if rope access inspection is replaced by visual (camera) drone inspections
- Further savings are possible when the drone/crawler can be made resident in the windfarm, as this further reduces logistical cost and allows for quicker deployment and faster and more frequent inspections.
- 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.
- The laser line scanner data can be used for storing size and position of blade damages. Therefore data is usable for automatic classification of blade damage.
- Ultrasonic detection technology is applicable for subsurface/internal damage detection in the blade like detection of delamination in the shell.
- Autonomous Drone-Crawler operations for inspections and repair is technically feasible but complex and needs more work

8.2 Recommendations:

- Miniaturization of drone and crawler, and drone residency in the windfarm, are needed for unmanned solutions to reach full O&M cost saving - and AEP increasement – potential.
- Regulatory reform is urgently needed to make autonomous robotized inspection/repair a reality, with a human in a control room ashore.
- Frequent maintenance with high accuracy robotized printing as repair of LEE needs to be studied as a way to keep blades in optimal shape (as close as possible to their design conditions), increase blade life and increase AEP.
- Increased monitoring to better identify the 'region of interest', where structural damage inside the blade might occur, and more attention of lightning damage, is needed.
- For an improved prediction of LEE, historical data is very important. This data must be used to learn from to get an early warning from trends preferably with the help of Machine Learning.
    - Previous studies have shown that performance data can be used for an early indication of degradation of the blades. Therefore, it is recommended to:
        - Improve the reliability of sensors on the Wind turbine (pitch, wind speed and direction)
        - Improve data registration by introducing automated data validation checks on the Breeze data
        - Introduce a digital twin where data sources are integrated, and data is stored in a central data lake.
        - Define performance dashboards based on smart rules indication the health of the blades
- To scale-up the robotized LEP transition coating process developed by Qlayers, improve its accuracy and repeatability the following steps are recommended:
    - Integrating a more precise pneumatic suspension system to suppress motion inconsistencies
    - For life-sized wind blades, the system should be able to move along the blade's span. This can be done with a robotic arm on rails or a revised concept.
    - For offshore maintenance, a crawler system could be developed that will move along the span of the wind-blade. The same system could be used indoors.

9. List of publications:

Detailed reports of workpackages:

- WP 1 sensor package development
- WP 2/3: autonomous drone, flight controller and crawler development
- WP 4: data processing
- WP 5: robotized print head development
- WP 6: erosion modelling and validation
- WP 7: Asset management strategies
- WP 8: Dissemination

Detailed reports by AIRTuB participants:

- Report by Demcon on flight path navigation (commercially confidential)
- HZUAS AIRTUB report
- AIRTUB report by Fusion
- Fusion report on windtunnel tests of the Reflex flight controller
- Fusion report on the hexacopter tests with the Reflex flight controller
- Fusion report on the hydra drone tests with the Reflex flight controller
- LM windpower report 'windtunnel testing of 3D printed LEP chamfering' (commercially confidential)
- NLR report "Remote Ultrasonic Inspection of Offshore Wind Turbine Blades - Automated Inspection and Repair of Turbine Blades (AIRTuB) - WP1"
- Fusion Reflex test table (commercially confidential)

All detailed (not-confidential) AIRTuB reports can be found on the project website: https://www.worldclassmaintenance.com/sub-project/airtub-automatische-inspectie-reparatie-van-turbinebladen/

Scientific reports:

- Remote Ultrasonic Inspection of Offshore Wind Turbine Blades, D.J. Platenkamp, V.S.V. Dhanisetty, A. Chabok, A.F. Bosch, NLR-CR-2021-177
- 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.

- 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.
- K. Vimalakanthan *CFD transition model for rough surfaces* TNO 2021 R12579, Public report, December 2021
- K. Vimalakanthan *Aerodynamic performance prediction of eroded and rough wind turbine blade sections using RANS CFD. EERA workshop on blade erosion from the perspective of loads, controls and aerodynamics*, December 14, 2022 SP4 WORKSHOP on Blade Erosion from the prospective of loads, controls and aerodynamics | EERA JP Wind
- I. Lallelis *Model Validation for Simulating the Effects of Leading Edge Erosio*n Hanze/TNO Student thesis report, January 2019.
- O. Shamir: *Analysis of LM wind tunnel measurements at erosion*. Public Hanze report, November 2020
- J. Nwaehie: *Automation of IRPWIND roughness experiment*, InHolland/TNO Student thesis report September 2020
- M.J. Vermeulen: *Erosion on wind turbine blade wind tunnel test,* NLR-CR-2021-516, September 2021
- Kisorthman Vimalakanthan, Harald van der Mijle Meijer, Iana Bakhmet, and Gerard Schepers *Performance modeling of eroded wind turbine blade using CFD*, Preprint for Journal of Wind Energy Science https://wes.copernicus.org/preprints/wes-2022-65/
- J.G. Schepers et al: *Summary of Airtub WP6.1 results*, TNO report
- Literature review of structural and non-structural wind turbine blade damage, Rogier Nijssen, Emilio Manrique, TNO 2020 R10402, September 10, 2020.

10. List of dissemination activities

AIRTuB meetings and events:

- 13-09-19 : Kick-off meeting AIRTuB project at HZ-UAS and Scalda in Vlissingen and presentation of the Smart Industry label
- 16-09-20 : Robotisation in Offshore wind – streaming live event from Futureland Maasvlakte met NWEA & Blauwe Cluster
- 21-09-21 : Annual AIRTuB event / TKI-WoZ Live – De KAAP Vlissingen
- 12-04-22 : AIRTuB dissemination event WP1 - TU Delft
- 20-05-22 : AIRTuB dissemination event WP5 - Qlayers - Delft
- 22-09-22 : AIRTuB dissemination event WP2 en 3 - HZ/Scalda – de KAAP Vlissingen
- 14-10-22 : AIRTuB dissemination event WP4, 6 en 7 - ENTRANCE Groningen
- 24-11-22 : AIRTuB final dissemination event NLR – Marknesse

Meetings in which the AIRTuB project was presented / discussed:

- 09-10-19 : Round-table at Offshore Energy E&C with SPARTA
- 07-11-19 : Deelname aan kick-off FIXAR innovatieproject
- 13-11-19 : Matchmaking sessie Wind meets Maak AYOP regio
- 11-12-19 : korte introductie tijdens Q-meeting Van Oord / Siemens
- 10-01-20 : Sustainable Service Logistics for OWF’s bijeenkomst – EnTranCe Groningen

- 16-01-20 : SPARTA Offshore Wind Benchmarking Workshop
- 04-02-20 : Presentatie op Matchmaking Day TKI WoZ 2020
- 18-02-20 : Presentatie at Conferentie Innovation in Offshore Wind Liverpool
- 30-09-20 : Masterclass Innovatie in Offshore wind – DOB Academy
- 25-11-20 : Grensoverschrijdende Samenwerking - Seminar Platform Energy Port Zeeland

- 13-04-21 : Feestelijke opening de KAAP Vlissingen
- 22-06-21 : Blade maintenance event
- 20-10-21 : Maintenance Technology and Robotics event - KIC-MPi
- 11-04-22 : Werkbezoek Ministerie van Economische Zaken en Klimaat (M. Adriaansens) - Vlissingen
- 14-04-22 : Nacelle-Go-live event - Vlissingen
- 24-05-22 : Studiebezoek Virginia Coastal Policy Center (William & Mary Law School) - Vlissingen
- 08-06-22 : Bezoek delegatie OWIC (samenwerkingsovereenkomst getekend) - Vlissingen
- 23-06-22 : Presentatie bij het DroneWest event – Oostende
- 15-09-22 : Presentatie bij de 'ontbijtbijeenkomst Platform EnergyPort Zeeland'
- 21-09-22 : Tribologie event by "Bond voor Matrialenkennis'- Vlissingen

- 03-11-22 : Aanwezigheid bij en promotie van Zephyros en AIRTuB op ‘De dag van het Klimaat akkoord’ - Utrecht
- 01-12-22 : Kerstborrel PEPZ (samen met Orsted) en internationale RVO delegatie in de KAAP – Vlissingen