AIRTuB

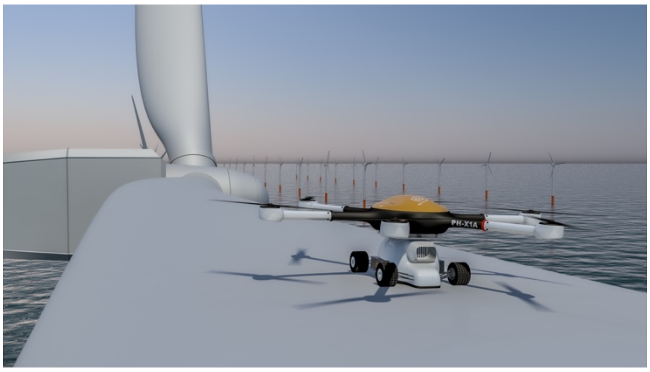
Report HZ UAS activities 2019-2023

ENGINEERING

2023-01-25

AIRTUB

REPORT HZ UAS ACTIVITIES



GUNSING, J.
BECKERS, M.
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DATA SCIENCE
ASSET MANAGEMENT
ENGINEERING

2023-03-03

VLISSINGEN/MIDDELBURG

VERSIE 1.0

STATUS: FINAL

INHOUDSOPGAVE

1. Project details

- Hogeschool Zeeland, University of Applied Sciences, and Scalda
  - Participating persons
    - HZ & Scalda:
      - WP2 & 3
        - Edward Mouw
        - Gillie Maas
        - Leo Blok
        - Joshua de Jong
        - Ronald Eijlers
        - Peter van der Heide
        - Gerben Huiszoon
        - Jos Gunsing (MaromeTech; outsourced activity)
        - Martijn Crombeen (Crombeen Robotics)
        - Other colleagues involved
        - Scalda (formally outsourced activity in WP2 & 3):
          - Ronald Schroevers
          - Kasper de Feijter
          - Other colleagues involved
      - WP6 (HZ participants):
        - Mischa Beckers
        - Loek van der Linde
        - Other colleagues involved
      - WP7 (HZ-participants)
        - Rob Schoenmaker
        - Albert Repko
        - Padraig Naughton
        - Other colleagues involved

2. Final report on the contents of the project

- **Summary**

  - WP2 & 3
    - Leading WP2 an WP3 overall
      - System architecting/interfacing between partners WP2/3 and WP1 (sensor development)
    - Development of crawler and test equipment
      - Connected to drone
      - Carrying internal damage sensor
  - WP6
    - Focus was on machine learning to predict LE erosion classes
    - Training data was used to create the prediction model
    - For this purpose several machine learning methods were compared
    - Validation
    - For details see: 2022-10-27 Overall report_WP6_13_12_22; by HZ UAS with focus on WP6.2
  - WP7
    - Further development and application of TNO O&M planner tool on AIRTuB case
      - 3 scenarios investigated
        - 1 rope access
        - 2. Drone inspection laser line scanner (3D, high resolution) ; repair rope access
        - 3. Drone inspection laser line scanner (3D, high resolution), internal damage sensing in indicated locations, repair with rope access
    - Detailed report available:
      - WP7 Business case report, December 21, 2022 by Repko, HZ and Dighe, TNO

Fig 1. Final AIRTuB event November 24, 2022 at Marknesse

- **Introduction:**

- WP2 & 3
    - In the early stage of the AIRTuB developments the key question for developing the equipment was:
        - How small and how precise should the relevant defects be measured?
            - The size and accuracy determine the size (volume/mass) of the sensor system
        - When the first ideas were generated in WP1 with respect to size and accuracy of the sensor the size of the drone and the size of the crawler could be determined.
        - Meanwhile concepts could already be developed in WP2/3 and feasibility models be designed/built and tested
    - In WP2 and WP 3 (HZ WP leader for both WP2 and WP3), Demcon, NLR and Fusion Engineering worked closely together in order to develop a drone plus crawler. In WP3 we work closely together also with WP1; TU Delft and another department of NLR to integrate:
        - Drone plus external damage sensor package
            - laser line scanner
                - Leading edge inspection
        - Drone plus crawler
            - Crawler carrying internal damage sensor package (ultrasonic sensor)
                - Structural damage sensor

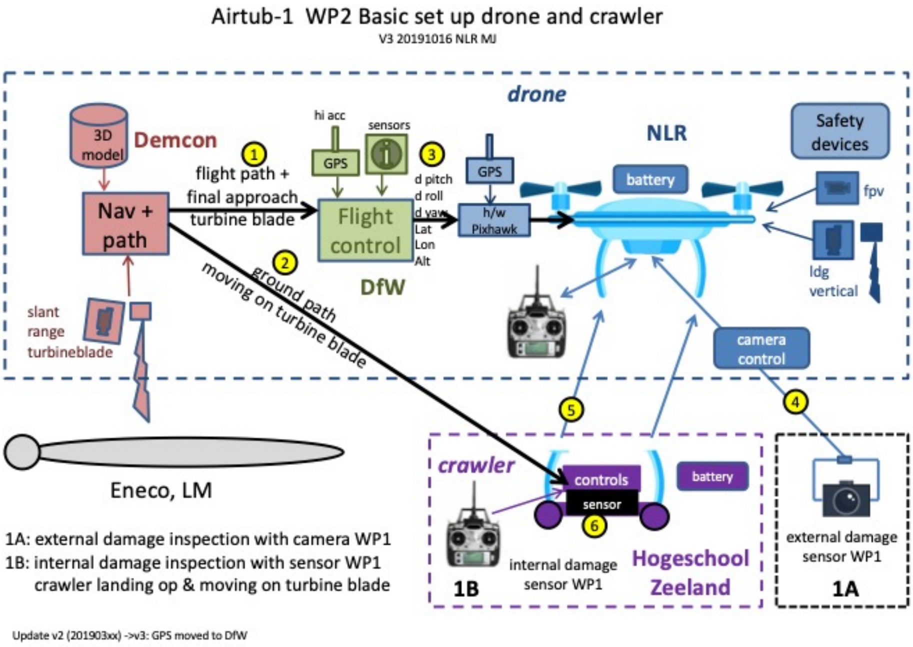

Fig.2. Basic architecture drone-crawler-external damage sensor package

- For navigation purposes Demcon developed a lidar for making a scan of the blade and leading edge contour. In combination with the GPS data a flight path can be generated along the leading edge and towards a landing area.

Fig.3. Lidar sensor for navigation path planning purposes (Demcon Unmanned Systems)

- Fusion is involved in developing a flight controller which is specially equipped to deal with heavy wind gusts, which is evidently an advantage when flying close to and /or lading on a wind turbine blade.

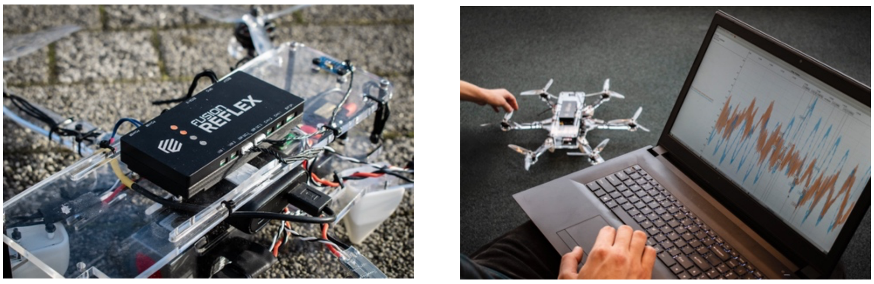

Fig.4. Flight controller for gusty wind conditions (Fusion Engineering)

- The crawler will be developed by HZ and Scalda in such a way that it can operate completely independently from the drone. In an earlier stage it was thought that the drone would be carried by the crawler when travelling on the blade but this is a too big risk/challenge. The drone will be equipped with a landing gear with locking devices to hold the crawler/external sensor package safely during flight/landing and take off and which enables easy/safe release and pick up of the crawler.

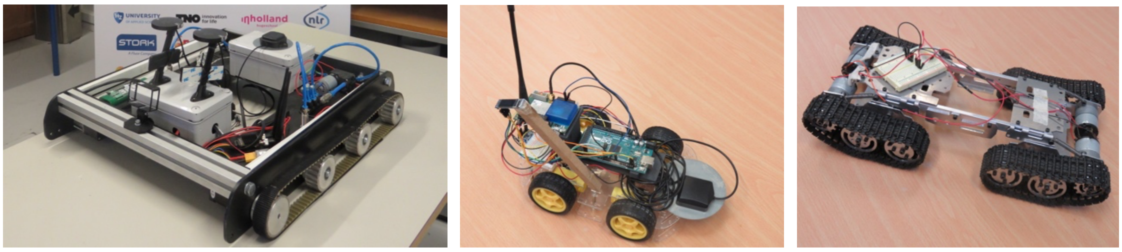

Fig.5. Feasibility models for crawler development (HZ UAS and Scalda)

- Several drones have been chosen by NLR to fulfil the requirements for flying with the laser line scanner and with the crawler/sensor package. In Both cases the lidar sensor is designed to be combined with several types of flight missions/drones. This also accounts for the Fusion Flight controller.
    - The flight controller development was on the critical path. For risk mitigation purposes we also had the possibility to apply conventional flight controllers

Fig.6. AIRTuB and testbed drone with laser line scanner (leading edge erosion damage TU Delft) (drones: NLR)

- Test equipment was developed by Scalda in order to test the crawler on a wind turbine blade under several circumstances for testing at the Kaap, Vlissingen
- Test wind turbine blade available at Marknesse
- At the end of the project we have following demonstrated prototypes:
    - 1 operational big drone; up to 60kg MTOM
        - Flying and landing with crawler
    - 2 operational drones; 15-20kg MTOM
        - 1 Flying with conventional flight controller and laser line scanner
        - 1 Flying with Fusion flight controller
    - Lidar sensor and software for flight path generation
        - Demo with help of film
    - 1 crawler stage 2: able to carry sensor package
        - Inspection demo on blade
    - Test equipment:
        - Mobile platform with 2 deg of freedom 22 m windturbine blade (tilt and pitch); available at the Kaap
        - Static 22m wind turbine blade at NLR, Marknesse
        - Both wind turbine blades were supplied by LM Windpower

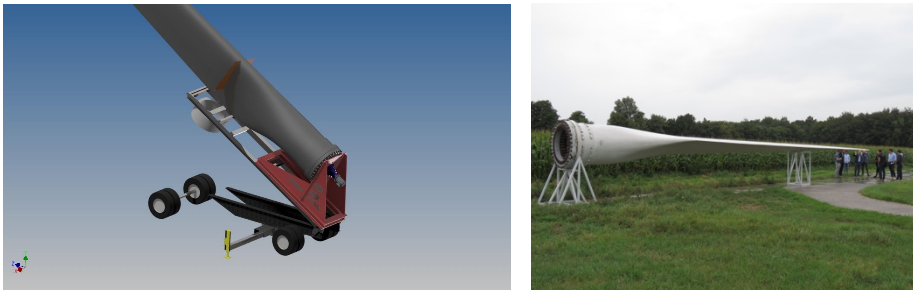

Fig.7. 22 m Windturbine blade: sketch for mobile platform (Scalda) and static test rig at Marknesse (NLR)

- Eneco has had the role of the asset owner and would originally also supply test time on onshore and offshore wind turbine farms apart from also supplying partical information to check the use cases with and also data for WP4 and WP7 . Due to lead time issues the tests on the onshore and offshore wind turbines could not be performed
- Especially with WP1 a close cooperation is necessary. The WP leaders from WP1 and WP2/3 participate in each other's WP meetings to keep the communication lines short.

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WP1 General

- The WP leaders from WP1 and WP2/3 participate in each other's WP meetings to keep the communication lines short.

- **WP 1.2. up to 1.6**: mainly impact on WP1.4 architecture of sensor package

  - HZ is involved in these WP's for reason that both the internal and the external damage sensor packages the sensor package has to be integrated in the crawler and drone so packaging in terms of volume/sizes, masses, center of gravity, communication protocols (both hardware and software) are important discussion items; also range and ways of operation of the sensor package are important issues to get agreement on. At this moment the designs are more or less complete and we are finetuning the interfacing both mechanically and electronically. The designs plus software message protocols will be detailed in the next months. The overall architecture and use cases are known

    (e.g. scanning or step inspection; how to deal with the involved forces, necessary for sensing, between sensor and turbine blade.

- **WP6**
  - WP6.2 The goal is to automatically classify the blade morphologies monitored from the scanners developed in WP1 into erosion categories, or classes where moreover a repair strategy for these erosion classes is implemented in a decision tool. The classification model has been determined and the decision tool can be based on this

model sing machine learning to classify LE erosion. Firstly, a suitable framework that defines relevant classes was defined, given the context. From literature such frameworks are available. A framework as defined by Gaudern (Gaudern, N. (2014). "A Practical Study of the Aerodynamical Impact of Wind Turbine Blade Leading Edge Erosion", Journal of Physics: Conference Series; 524: 012031.) was selected that defines five classes. Membership of a class is defined by area (mm) and depth (mm) of the erosion, and ranges from 0.1mm depth / 2mm diameter (class 1) to 1.2mm depth / >500mm diameter (class 5). For detecting erosion a sensor is needed that is capable of generating data for both depth and diameter. A specific requirement is its resolution, since a depths as low as 0.1mm need to be detected. WP1 did a literature study for appropriate sensors and from that, matching context to specifications, a 3D laser line scanner was selected.

Class	**Name**	**Depth (mm)**	**Diameter (mm)**
1	Small pits	< 0.2	< 2
2	Pits	< 0.2	2 - 5
3	Small gouges	0.3 – 0.5	5 - 20
4	Gouges	0.5 – 0.8	20 - 50
5	Delamination	> 0.8	> 50

Table 1. Damage classification classes

- **WP7**
    - See chapter 1 WP7 Business case report
        - Application of TNO O&M model on 3 baselines
        - <u>Main question</u>:
        - How do the benefits, costs and risks of inspection (and repair) methods with the AIRTuB drone compare to those of the current inspection methods of the Amalia wind park?
        - Sub questions
            - What types of failure have occurred during the current service life and what consequential damage have they had?
            - Which measures have been taken? Which inspection and repair techniques have been used? What Asset Management (AM) strategy has been followed?
            - Which AM strategy is foreseen for the remaining life? What is the estimate of the future damage pattern? What is the estimate of future developments in terms of inspection and repair?
            - What are the advantages and disadvantages of the current inspection techniques?

            - What are the business goals of using the developed automated blade Inspection technology of the AIRTuB project?
            - What are relevant predictive maintenance performance indicators?
            - What are the concrete input data of the two baseline scenarios for the business case comparison?

- **Objective/goal**
    - **WP2 & 3**
        - Successful cooperation NLR, Demcon, Fusion Engineering, HZ and Scalda incl. MaromeTech (WP leader Jos Gunsing)
        - redesign and tests of several drones
        - Integration of Fusion flight controller in testbed drone (delayed, not tested in big drone)
        - Successful design and test with outdoor and indoor navigation modules; indoor for test purposes (indoor flying has less legal restrictions)
        - Lidar test near wind turbine blade successful
        - Successful design and test of vacuum devices for blade holding/clamping mechanism
        - Phase 2 crawler; tested under drone and tested on blade including sensor package while holding and moving
        - Scalda realized a mobile platform with tilt and pitch function for the available 22m wind turbine blade at De Kaap; on a second hand trailer a support is being built such that the blade can safely be:
            - Pitched over 360 degrees
            - tilted/rotated over an angle of over 30 degrees
            - Moved to other nearby locations such as inside/outside De Kaap
        - involvement of students:
            - HZ
                - Overall 90 + students involved
            - Scalda
                - Overall approx.. 30 students involved
        - Involvement of other university of applied sciences
            - Avans University of Applied sciences has joined the project with the minor Aerospace Engineering & Maintenance during autumn 2020 and 2022 and several involved student groups delivered a working demo of the motion and clamping mechanism for the crawler (demo January 2021) ; in January 2023 they delivered a lot of test results for the crawler stage 2 plus several proposals for further improvement

Fig.8. Students involved in projects (HZ UAS, Scalda and Avans UAS)

  - **WP6**
    - WP6.2:
      - To develop a procedure to classify an arbitrary blade erosion into different categories, or classes, using machine learning
      - (To develop a repair strategy for different erosion classes and implement it into a decision tool)
  - **WP7**
    - Obtaining insights in business model and the costs and benefits from the developed scenarios in the AIRTuB project:
      - Details see WP7 Business case report
- **Way of working**

  - **WP2 & 3**
    - In general:
      - Regular meetings
      - Contacts inbetween
      - Discussion and work distribution leading to :
        - Use cases
        - Requirements
        - Functional decomposition
        - Risk analysis
        - Risk mitigation actions
        - Sharing results
        - Combined testing
      - Working towards demonstrator model which means
        - Lean interfacing between modules /functions
        - Each function can operate and communicate independently
        - This will not lead to an optimal product but to a demonstrator in time which helps to determine the requirements and the specifications for a real product
    - HZ:
      - technical lead for WP2 and WP3
      - development of crawler with teacher/researchers and students
    - Scalda:
      - Development and technical support for crawler
      - Development, building and test for mobile wind turbine blade tilting and pitching platform

- **WP6**
    - WP6.2
        - With the setup for data acquisition, as described in Introduction, ready, we had to wait for a rather long time before the first scan could be made. The first scan involved a blade that was already hugely damaged for the complete surface (it all was erosion class 5). Nevertheless it gave us the opportunity to study how to do proper data acquisition, initial data understanding and develop ideas on how to "slice" the complete images into smaller chunks of data. The latter was necessary to be able to perform the classic machine learning pipeline on this specific use case. It resembles the well-known computer vision case in which labeled images are given to a machine learner to create a prediction model. Later we received a second scan. It was a scan of a specific LE part of a blade. The part was 1m in length. A visual inspection indicated that several erosion classes were present, but probably not beyond class 3. Using more specific inspection enabled us to label the erosion on the complete scan more specifically. It turned out that actually only class 1 and 2 was present. Which in itself was seen as beneficial: if the model was able to classify those more "difficult" categories correctly then the assumption was that classes 3 and beyond should not be that difficult for the model.

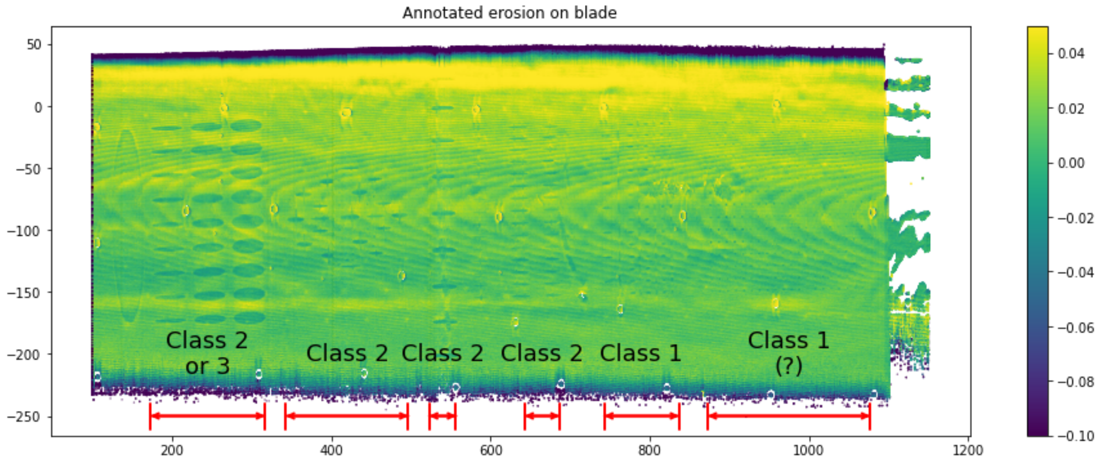

Fig.9. Scan of 1 m section of blade. Displayed is the "depth" as a varying color (z-coordinate, "color-scale") at a specific location (x-, and y- coordinate resp horizontal and vertical). The scanning process starts at about 100 mm and ends at about 1100 mm in the x-direction.

        - Hence, about 1 m of blade was scanned. In the y-direction it appears that the blade was not exactly in the middle of the camera filed. However, for the process this was no problem. With respect to five classes as defined in the framework by Gaudern , erosion classes 1, 2 and (possibly) three could be found in the scan.
        - 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 (using a Support Vector Machine classifier) was used on the test set, which resulted in an accuracy of almost 65%.

- This looks very promising, and it provides possibilities for spin-off and follow-up activities. However, 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.

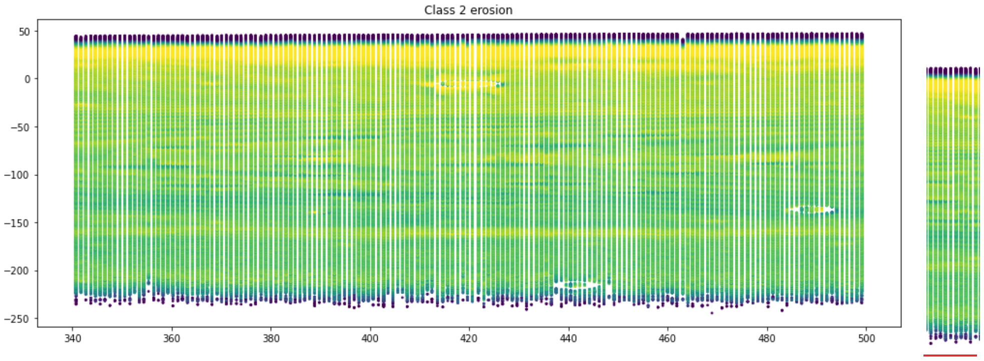

Fig.10. Sliced scan of 1 m section of blade; subsequently sliced into pieces of 10 laser line scans; since the image is a collection of laser *line* scans, we can select a subset of line scans to display, or store it.

- **WP7**
  - sources are used for the input of the business case?
    - Input from other WP’s
    - Data from Amalaia windpark
    - Data from interviews; several parties
    - TNO O&M model for windparks
  - How is the business case/ cost analysis of the scenarios constructed?
    - what is included and what not?
      - See report WP7 Business case report
  - How is the validation with experts been done?
      - For details see WP7 Business case report

- **Results/deliverables:**

    - **WP2 & 3:**
    - **WP2:** General
      - HZ has a technical leading role in WP2 and WP3 and has a direct contact line with WP1 in order to integrate the internal and external damage sensor packages in the drone and/or crawler

    - **WP2.1.** Definition of use cases

    - use cases for flyby and on-the blade inspection available

- **WP2.2.** Definition of architecture
    - The gross distribution of functions/modules/building blocks of drone, crawler including lidar sensor and flight controller is available

- **WP2.3.** Design of experimental set-up
    - Several feasibility models have been realized for drone and crawler including lidar sensor and flight controller test; also several test set ups for feasibility and prototype tests based on 22m wind turbine blades are available both static(Marknesse) and mobile (with pitch and tilt)

Fig.11. Mobile platform with rotatable/pitchable 22m blade

- **WP2.4.** Development of experimental set-up
  Based on results several steps have been taken to come to a definite drone and crawler prototype version including the lidar sensor and flight controller;
- **WP2.5.** Lab testing, optimization and redesign
    - Mny tests have been carried out with drone/crawler, lidar sensor and flight controller
- **WP3:**
    - The on- and offshore test have not been taken place;
        - Delays due to covid 19 measures
        - Delays in the development of the Fusion Flight Controller
        - Instead: big demo event November 24 2022 in Marknesse
- **WP6:**
    - WP6.2
        - All source code used is available as Jupyter notebooks, as well as the developed and used workflow (graphic)

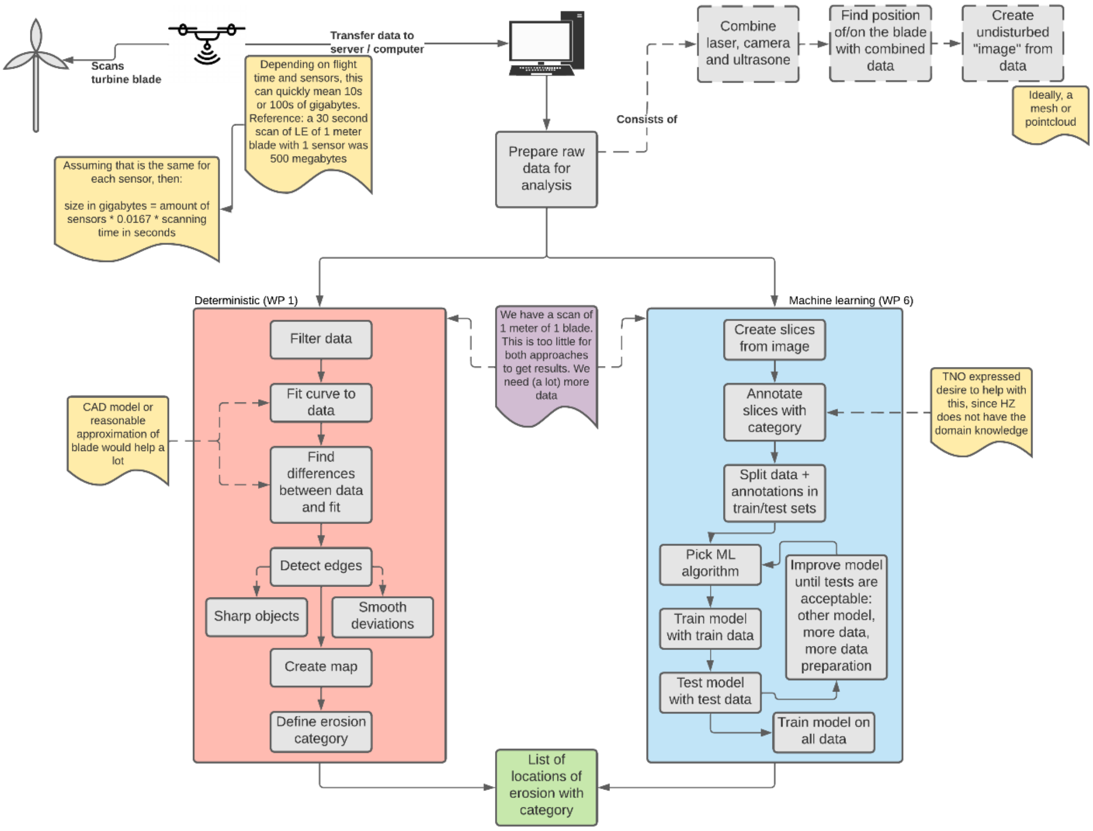

Fig.12. Work flow for data processing

- **WP7:**
  - De results (conclusions &recommendations) can be found WP7 Business case report chapter 7 and 8
  - Calculation model based on TNO O&M model

- **Of the project itself**
  - WP2 & 3:
    - HZ: prototype/demonstrator of crawler able to:
      - Crawl over blade including sensor package carrying out inspection while clamping with vacuum to the turbine blade
        - Teleoperated
      - Crawl in and out drone payload carrying gear (combined with landing gear) including safe connection drone-crawler operated from crawler
  - WP6
    - WP6.2
      - The 1m part of the actual blade that was used was artificially “aged” using sandpaper that was glued to the surface. Despite this is artificial aging process, the erosion corresponds to what is found on blades taken from wind parks (profiles and characteristics of erosion classes, are described in literature, based on real-life

inspections). Therefore, we strongly belief that the method used will work correspondingly on real-life aged blades. Moreover, the method used was capable of also classifying erosion class 1 cases. These have depths of 0.1 - 0.2mm! This improves confidence that the method as used is promising.

        - Although the method as developed and used already proved to add value, the accuracy of classification is not sufficient. Given the limited amount of data we have up till now this did not come as a surprise. To improve accuracy we need to add more data for the machine learner to be able to learn the appropriate patterns. This involves data of 1) more (different) blades, 2) larger parts of the blades and 3) representing examples of all 5 erosion classes. In that way we should be able to create more accurate predictions (classifications). On top of that the created model should be more robust, and able to generalize better.
        - All source code used is available as Jupyter notebooks, as well as the developed and used workflow (graphic)
    - WP7
      - See WP7 Business case report chapter 7 and 8

- **Possibilities for spin-off and follow-up activities**

  - WP2 & 3
    - HZ/Scalda
      - Strenghtening of combined research and education of Sclada, HZ and also UCR (discussion started)
      - Involvement of MKB companies in wind turbine maintenance
      - Further contribution to AIRTuB2 and other projects in the field of maintenance and robotization in the energy transition field

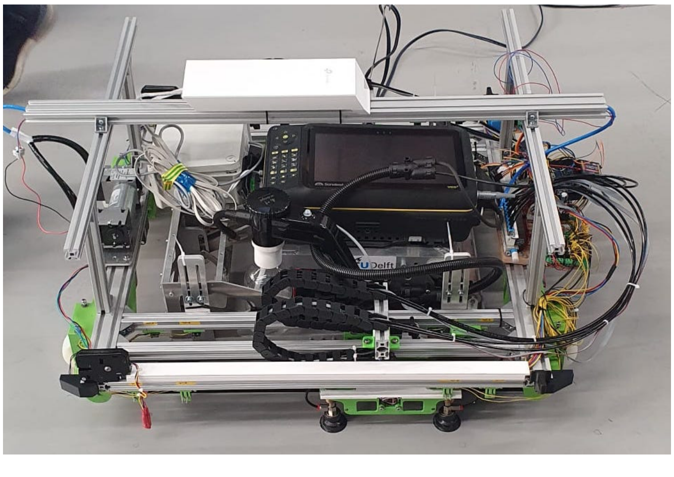

Fig.13. Crawler (HZ UAS/Scalda) including external damage sensor (TU Delft)

- **WP6**
  - See paraghraph: “of the project itself”.
- **WP7**
  - Further detailing of input parameters including up to date figures/data

- **Discussion**

  - **Conclusions and recommendations**

    - **WP2 & 3**
      - A drone, crawler including sensor package have been developed and demonstrated successfully.
      - A lidar sensor including path planning ahs developed and demonstrated successfully.
      - A flight controller has been developed and demonstrated successfully.
      - In a follow-up project we would have a plan B scenario available for critical developments (in our case the Fusion flight controller development)
      - Strongly dependent on the internal sensor development a development of drone and crawler towards lower mass and volume will be possible; mission time and agility (=also safety) will benefit from this.
      - Further development of crawler to be able to crawl on the leading edge for internal damage inspection and for leading edge repair i.e. new layer on eroded areas. Another addition can be the detection of loose Leading Edge Protection shells

Fig.14. Drone with crawler on landing platform and crawler/sensor package on 22m wind turbine blade

    - **WP6**
      - <u>WP6.2</u>
        - The 1m part of the actual blade that was used was artificially “aged” using sandpaper that was glued to the surface. Despite this is artificial aging process, the erosion corresponds to what is found on blades taken from wind parks (profiles and characteristics of erosion classes, are described in literature, based on real-life inspections). Therefore, we strongly belief that the method used will work correspondingly on real-life

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- **WP7**
  - See WP7 Business case report WP7 (chapter 7 and 8)

3. Execution of the project

- **The problems (technical and organizational) that occurred during the project and the way in which these problems were solved**
  - **WP2 & 3**
    - Covid 19
      - Especially in spring 2020 hardly any prototyping and experimental work could be carried out due to the lockdown of HZ and Scalda. The delay is still present
    - Execution of actual inspections/tests on offshore windturbineblades
      - Scope of project limited ; still the feasibility of the individual modules has been carried out and several of them also in combinations:
        - Drone/external damage sensor(Laser line scanner)
        - Drone/crawler: flight and release of crawler
        - Crawler/internal damage sensor (ultrasound)
    - Blade holding/clamping mechanism
      - On a small scale the blade holding mechanism with vacuum application works but it has not been proven on a scale sufficiently to deal with a big crawler in more severe wind conditions including wind gusts; the work in the next year will focus on these issues to make sure that the effectiveness will be proven. In September 2021 test will be carried out with a phase 2 crawler (both upgraded mechanics/electronics and Software) in parallel other holding/clamping mechanisms will be engineered and tested as backup solutions
    - Small mass budget for crawler functionality
      - The sizes required from the sensor package WP1 are big (sensor package of 500x500x500 mm at a mass of max 10kg) ; the size will be smaller than this; estimate 300x300x600 with a slightly bigger mass. The impact will be discussed with NLR
      - Total mass budget for the crawler functionality is 5 kg including the attachments for the sensor package and the possibility to work with vacuum plus the attachment mechanism with the drone; the mass will probably be higher than the aimed 5 kg; still under discussion
  - **WP6**
    - WP6.2
      - The main problem in WP6.2 was related to uncertainties about available data. Data could only be collected after the selection process for an appropriate sensor was finalized. After that a blade had to selected and transported to the corresponding lab. There the sensor had to be installed, configurated, calibrated etc., which is not a trivial process when using a 3D laser line scanner under these circumstances. Finally, it turned out that the initial blade that was used actually was a class 5+ blade as a whole. Fortunately, it helped in defining the process/method to acquire and process data to be able to do

machine learning. Hence, when we received the raw data form the 1m blade that was artificially "aged" we could immediately start implementing and testing our method.

- **WP7**
    - Accuracy of data from (older) windfarms not detailed enough (time sampling with too low frequency to find clear relations of blade damage, delivered energy and wind force)
    - Execution of actual inspections/tests on onshore/offshore windturbine blades

- **Explanation of changes to the project plan**
    - **WP2 & 3**
        - Delays w.r.t. Covid 19; estimated 3 to 6 month
        - Leaving out the onshore and offshore tests as communicated earlier
    - **WP6**
        - WP6.2.
            - Limited data available
        - Leaving out the onshore and offshore tests as communicated earlier
        - No data from actual inspections with drone/crawler /sensor packages on onshore/offshore windturbine blades
    - **WP7**
        - Leaving out the onshore and offshore tests as communicated earlier
        - No data from actual inspections with drone/crawler/sensor packages on onshore/offshore wind turbine blades

- **Explanation of the differences between the budget and the costs actually incurred**
    - **WP2 & 3**
        - **To be determined and if necessary explained**
    - **WP4**
        - **To be determined and if necessary explained**
    - **WP7**
        - **To be determined and if necessary explained**

- **Explanation of the way of spreading knowledge**
    - **WP2 & 3**
    - Active involvement in September 1, 2020/August 31, 2021:
        - Masterclass Offshore Wind, Innovation in Maintenance
            - September 30, 2020
        - 2020 Zephyros annual congress/webinar:
            - Zephyros/AIRTuB/Mars4Earth
            - September 16 2020
        - Demo-session crawlerplatforms
            - AVANS, HZ and Scalda
            - January 28 2021
        - Demo session Event windturbine blade maintenance
            - Zephyros/AIRTuB, Mainblades, NLR, HZ, Scalda
            - July 22 2021
        - Demo Session Crawler, De Kaap, Vlissingen September 22, 2022
        - Demo Session AIRTuB, at NLR Marknesse, November 24, 2022

- **WP6**
    - Public event on October 14 at Hanze UAS. Results of both WP6.1 and 6.2 have been discussed in detail and experts from other institutes gave guest presentations as well
    - Demo session Event windturbine blade maintenance
        - Zephyros/AIRTuB, Mainblades, NLR, HZ, Scalda
        - July 22 2021
    - Demo Session AIRTuB, at NLR Marknesse, November 24, 2022
- **WP7**
    - Demo Session AIRTuB, at NLR Marknesse, November 24, 2022

- **Explanation PR project and further PR possibilities**
    - **WP2 & 3**
        - AIRTuB Crawler at events
            - Visit of minister Robbert Dijkgraaf to Scalda, HZ and UCR
                - Pitch for minister Robbert Dijkgraaf at JRCZ (Joint Research Center Zeelandl Scalda, HZ and University College Roosevelt, Middelburg. November 14, 2022
            - Opening of JRCZ (Joint Research Center Zeelandl Scalda, HZ and University College Roosevel), Middelburg. December 15, 2022
            - Several events at De Kaap, Vlissingen. Autumn 2022
    - **WP6**
        - Demo Session AIRTuB, at NLR Marknesse, November 24, 2022
    - **WP7**
        - Demo Session AIRTuB, at NLR Marknesse, November 24, 2022

Fig 15. Final AIRTuB event November 24, 2022 at Marknesse , all WP teams , public plus demonstration models near static 22m wind turbineblade test rig