FINAL REPORTING

Leading Edge Roughness on Wind Turbine Blades

– Quantifying Leading Edge Roughness

*Journal Nr.: **64015-0046***

June 2019

Contents

1. 1.1 Project Overview

Project title	`Leading Edge Roughness on Wind Turbine Blades`
Project identification (program abbrev. and file)	`64015-0046`
Name of the programme which has funded the project	EUDP (Wind Energy)
Project managing company/institution (name and address)	Power Curve ApS
Project partners	Power Curve ApS (PC) Aalborg University (AAU) Technical University of Denmark (DTU) Danish National Metrology Institute (DFM)
CVR (central business register)	25730453
Date for submission	30th June 2019

The "Leading Edge Roughness on Wind Turbine Blades Project" (LER Project) has been running from 1st of October 2015 till 30th April 2019 *(Originally 30th September 2018).*

The project period has been extended twice, first in 6 months due to a fire during the construction of the Poul la Cour Wind Tunnel at DTU, which was a key element in the project and later an additional month extension due to a damage in the wind tunnel during its first operational hours.

The project consortium consists of 4 parties and an advisory board:

- Power Curve ApS (PC)
- Aalborg University (AAU)
- Technical University of Denmark (DTU)
- Danish National Metrology Institute (DFM)
- Advisory board
    - Vattenfall
    - E.on
    - Stattkraft

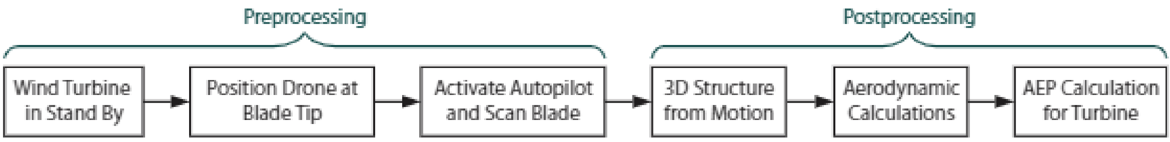
1.1 Nomenclature

- Annual Energy Production (AEP)
- Computational Fluid Dynamics (CFD)
- Leading Edge Roughness (LER)
- Structure from Motion (SfM)
- Unmanned Aerial Vehicle (UAV or "Drone")
- Work Package (WP)

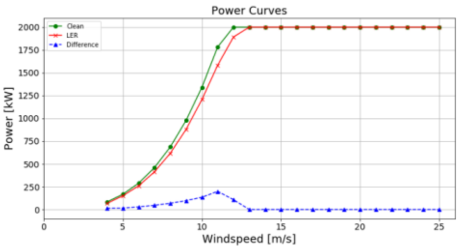
2. 1.2 Short description of project objective and results

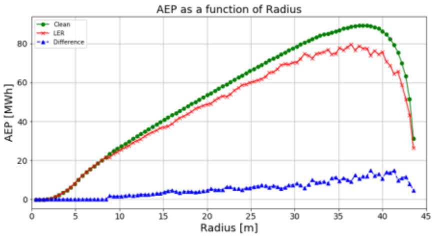
2.1 English version:

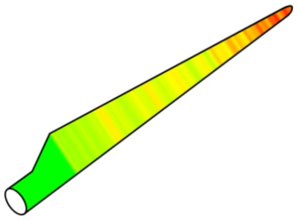
The scope of the project was to quantify LER and estimate the corresponding AEP loss on a given wind turbine. The objectives can be divided into pre-processing and postprocessing. The pre-processing objectives deals with obtaining high resolution pictures of the damaged blade to detect sub millimeter roughness. The postprocessing objectives deals with processing of the pictures which includes, obtaining a 3D model of the blade damages using Structure from Motion (SfM), aerodynamic calculations and AEP estimation. Below a flow diagram illustrating the general approach is shown:



Results: High resolution pictures of a blade damage are obtained on a test stand flying the drone manually, a 3D model have been created based on the pictures using SfM software. Aerodynamic calculations using made algorithms have been performed resulting in an estimated AEP loss for the given damage and turbine. Below is a result of a real life example/proof of concept from the project:

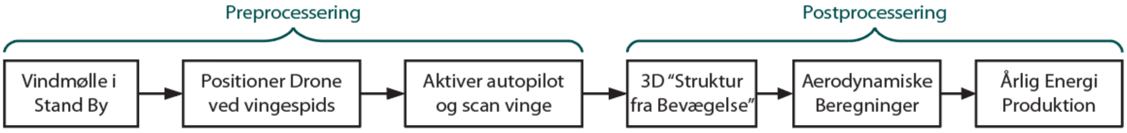




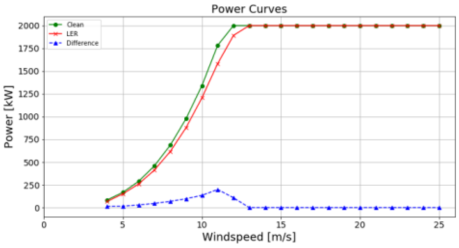


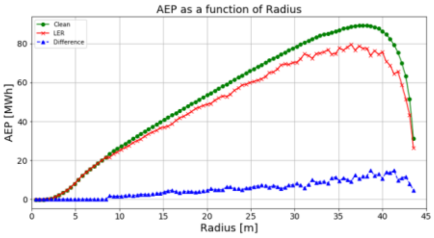
2.2 Dansk version:

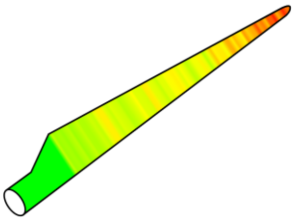
Projektets mål var at kvantificere LER (Forkants Ruhed) og estimere det tilsvarende AEP-tab (Årlig Energi Produktion-tab) på en given vindmølle. Målene kan opdeles i forbehandling og efterbehandling. Forbehandlingsmålene var at tage højopløselige billeder af den beskadigede vinge for at detektere ruhed under en millimeter. Efterbehandlingsmålene omhandler behandling af billederne for at opnå, en 3D-model af vingeskaderne ved hjælp af "Structure from Motion"/"Struktur fra Bevægelse" (SfM), aerodynamiske beregninger og AEP estimering. Nedenfor vises et flowdiagram der illustrerer den generelle tilgang:



Resultater: Højopløsningsbilleder af en vingeskade blev taget ved manuel flyvning af drone på en teststand, en 3D-model er blevet lavet ud fra billederne ved hjælp af SfM-software. Aerodynamiske beregninger med designede algoritmer er blevet udført resulterende i et estimeret AEP-tab for den givne skade og turbine. Nedenstående figurer viser et eksempel på resultater fra et scan af en virkelig vinge:







3. 1.3 Executive summary

Aerodynamic damages that changes the shape of a wind turbine blade and disturbs the designed airflow are often small compared to the size of the blade. Due to the blade design and nature of the airflow these damages tends to accumulate near the leading edge of the blade and are often referred to as Leading Edge Roughness (LER). No broad understanding and agreement exists in academia or industry on the impact of LER on aerodynamic performance and wind turbine AEP loss. The goal is therefore to develop a method to estimate changes in AEP based on the condition of the blade for wind turbine owners when deciding how to invest in compensation of the damages.

To quantify LER a comparison of the current wind turbine blade surface condition and clean blade is made. This is done based on high resolution pictures of the blade surface and using Structure for Motion (SfM) to obtain a 3D-model of the damaged blade. The 3D-model is divided into a number of 2D slices each 2D slice is by an algorithm compared to a test matrix containing a large catalogue of different damages to find the best match. Polars for both the clean and LER case are used as input to a BEM code calculating the AEP for both cases and thereby the AEP loss.

Different types of results have been achieved during the project e.g. academic documentation and algorithms to automate each step of the process have been developed. This includes algorithms for automatically running the SfM software with a given set of parameters to obtain the 3D-model, an optimization algorithm to match the 2D slices with the test matrix finding the polars and running the BEM.

The results can be utilized to obtain an estimated AEP loss based on high resolution pictures of a blade subjected to LER in an automated way. Furthermore the academic documentation serves as Ph.D material.

4. 1.4 Project objectives

The project was divided into work packages (WP) with distinct tasks and objectives and a WP leader to maintain the overview of the WP together with deliverables. The leader is seen in parenthesis after the WP. The other project partners have all been working across WP's to ensure knowledge transfer and project coherence and evolvement.

4.1 Project work packages:

- WP 0: Project management (PC)
- WP 1: Development of in-situ blade surface scanning equipment, roughness analysis and quantification algorithms (AAU)
- WP 2: Reference measurements of leading-edge roughness (DFM)
- WP 3: Predicting the aerodynamic performance and influence on annual energy production from roughness (DTU)
- WP 4: Full scale validation of technology platform (PC)
- WP 5: Implementing the knowledge into Power Curve for commercial exploitation (PC)

Short description of each WP (Taken from original project application):

WP0 Is planned to ensure smooth progress throughout the different project phases as well as effective dissemination of the project results. Power Curve will lead the project management.

WP1 Deals with 3D surface scanning including the development of a fit for purpose access system and surface roughness analysis and quantification methodology. Deliveries are specification of access equipment and sensors in one combined system. It will be based on commercially available drone technology. Development of software and workflow specification for converting scan data to 3D surface reconstructions and for generating quantitative parameters for roughness, and how they vary along the blade.

WP2 Will provide reference measurements of LER and specify an optical microscope with focus stacking for surface measurement. A software solution is developed for extracting data of the multiple focus shifted images. The microscope will be validated in its lower measuring range by comparison to a traceable confocal microscope. A physical object that fits both the new microscope and the drone based imaging system will be specified. It will be used for validation of the drone based imaging system and to estimate the uncertainty on the measurements. Selected blade sections will be directly characterized using the new microscope and indirectly by using the replication method. At least five sections of 'real' leading edges of turbine blades will be measured and characterized as calibration for the drone based measurements.

WP3 Predicts the LER-AEP effect through CFD analysis and experimental wind tunnel tests. Based on selected surface roughness types, the aerodynamic performance of blade sections is predicted using CFD. Based on these selected surface roughness types, tests are performed to investigate the LER-AEP effect and to validate the predictions carried out with CFD. Application of the different types of roughness and different types of vortex generators will be investigated. Based on the test results, the corresponding aerodynamic performance for wind turbine rotors is investigated including modeling of distributed roughness on the blade with e.g. more severe roughness at the outer part of the blade and less on the inner part. The predictions will be validated in WP4 full scale tests.

WP4 To validate the developed process a full scale test is performed on a turbine due for blade refurbishment within the project period. The validation is based on SCADA data for the test turbine prior to and after blade surface repair. The blade LER level prior to repair is measured and used to calculate AEP loss. After surface repair, the LER measurement is repeated as reference for 'clean case' AEP calculation. The field trials will be conducted in cooperation between all partners and E.On and/or Vattenfall. The Field trials will start approx. half way through the project to start delivering data for the consortium to develop upon. This approach ensures a strong business focus and end user involvement throughout the project.

WP5 Ensures technology transfer from research institutions to Power Curve for technical autonomy and commercial exploitation. As the majority of the development work is done outside Power Curve, an Industrial PhD student is hired by Power Curve to secure all critical knowledge and tools are well adopted into Power Curve. The PhD student will contribute with all available resources in the DTU and AAU work packages. At the end of the project it is important to conduct learning activities as a lot of the activities in this project will carry on after project completion. An evaluation and learning report is made for the continuous development and optimization of the product to fit end user needs.

For each WP a more detailed plan was prepared containing objectives, activities, description of work, role of participants and delivery dates of milestones. Below an example of this is shown for WP0

4.2 Project development

The project cooperation between all of the organisations have been excellent with no major disagreements during the project, furthermore each partner has fulfilled their role and completed the tasks and milestones in a satisfactory way for their respective WP. Additionally, the communication and cooperation with the EUDP administration have been good throughout the project.

The project generally progressed as expected and in accordance with the agreed milestones. A few realisations and problems was though encountered during the project. One of the realisations made was the work load/amount of development work associated with especially the UAV and an autopilot feature for this in WP1 had been underestimated. *See WP1 description for more details.* This resulted in some milestone delivery dates being pushed and a lot of time spend on the autopilot was still not sufficient and viable enough for full scale wind turbine test at the end of the project. Furthermore a crash with the drone during outdoor testing in the development phase resulted in some broken parts that had to be replaced delaying the process even further.

Some unforeseen problems were encountered during the project. One was the Poul la Cour Wind Tunnel fire resulting in postponing the project. Another was the availability and access to turbines where the process could be tested in “real life” conditions which resulted in a test rig being created in the backyard of Power Curve (PC). The test rig consisted of a gantry with the tip of a real blade hanging.

5. 1.5 Project results and dissemination of results

5.1 WP0 - Project management, dissemination and exploitation

A steering committee was formed in the beginning of the project with one person from each party of the consortium. A steering committee meeting was held every 6 months where the committee met in person, gave a status of the previous 6 month and plans for the next 6 months. The objective of the meetings was to ensure that the project was on track. If changes were necessary the steering committee could approve such. A suitable amount of time was predefined for all participants to ensure that everyone presented.

To ensure effective communication and knowledge transfer between all project participants and across WPs during the project some distinct actions were taken. This was necessary to ensure a good process for all parties and coherence throughout the project. There have been a lot of work across WPs meaning that even though a WP leader from one organization was appointed, multiple participants from different organizations often worked together in the WP. Due to this, regular meetings were scheduled to discuss the progress of different milestones for efficiency an agenda was made prior to each meeting ensuring that the relevant topics were discussed. In addition to this, timeframes for each topic were agreed upon across all participants to ensure all topics were covered within the scheduled meeting time. These meetings were planned via emails or Doodle votes in good time to ensure a high meeting attendance. The task of referent circulated between the parties for each meeting. All parties have handed in relevant documents before the deadlines in most cases, with only small delays at sometimes.

Especially WP1, WP2 and WP3 contained a lot of work. Small projects were made within the WP's with relevant personnel from different parties. As an example, three persons, one from PC, one from AAU and one from DFM did a small project of validating the SfM measurements that also resulted in an article (during submission, not published, still confidential). Most of these small projects resulted in papers/articles or conference presentations. Making scientific work across scientific fields was a great benefit to all parties as these things tends to be isolated to a certain field.

There have been no conflicts during the project because of well-timed decisions and general agreement in the steering committee. No decisions without approval of each party were made. The relevant personnel were consulted during each decision made in the steering committee, which resulted in no conflicts.

The project is not on a patentable stage yet, but that will hopefully come in the next project, AeroMax, which is still in review.

Work and knowledge have been shared and exploited through e-mail and online drives. The universities have a much stricter IT limitations on which online storage to use than DFM and Power Curve. As Power Curve was using "Dropbox" and the universities were only allowed to use "Google Drive", some minor difficulties had to be overcome, as it is no little task to merge data and files to new platforms. It worked out by sharing documents through the cloud services, but a lesson to future projects is to agree on a common service to use.

Disseminations has been through a wide range of conferences and scientific papers/articles in various fields and throughout the project. See the list of dissemination in the appendix.

Specific Milestones:

- **Hold 6 project meetings**
    - The meetings were held every 6 month, all in person. A lot of smaller meetings were held in the WP's as well, for relevant personnel, either online or in person. Especially AAU and PC has spent many hours together during the project.
- **Dissemination and exploitation plan approved by the Steering Committee**
    - All plans were approved by the steering committee and nothing was published without approval. Some publications have been held back to have a natural order in the publishing of findings, to be published later in the project. Some work is still pending, under review or being finished as of the delivery date of this report.

5.2 WP1 - Development of in-situ blade surface scanning equipment, roughness analysis and quantification algorithms

5.2.1 Development of 3D Surface Scanning (AAU):

Objectives:

In order to obtain quantitative knowledge of the AEP loss resulting from leading edge roughness the whole project idea was centered around performing 3D scans of the patches on the leading edge of a blade. From the very beginning of the project, being able to acquire such 3D scans at a sufficient accuracy and precision was a necessary premise.

Hence, the main objective of this part of the project was to develop the techniques and methods required to obtain 3D scans using sensors that could be mounted on a drone:

- Scanning must be possible to carry out from a drone
- Scanning must be able to deliver 3D reconstruction of patches of leading edge
- Scanning must be at sub-millimeter resolution to capture roughness

In the ideation phase of the project it was determined that 1) the scanning did not have to be real-time, i.e., it would be totally acceptable that the scanning required significant post-processing before passing results to the AEP loss evaluation, and 2) it was totally acceptable if the scanning process required the turbine to be parked for the duration of the scanning, as long as the scanning process was at least less time-consuming than rope inspection.

Main activities:

The activities in the work package can be divided into 3 parts: 1) deciding on a scanning technology, 2) understanding the accuracy/precision performance of the scanning technology under various conditions/parameters relevant for the application scenario, 3) deciding on the best compromise of scanning conditions/parameters so as to optimally serve the purposes of the project (being able to quantify AEP loss resulting from leading edge roughness).

Deciding on scanning technology

Even before the project started we expected that laser-range finding and LiDAR would not be sufficiently accurate for the project; at least not with devices that were small and light enough to be carried by a drone. Nevertheless, initially in the project we investigated quite carefully the state-of-the-art in the area, as well as the specifications of the available products. The conclusion was that stereo vision, sonar-based ranging, laser-range finders, and LiDAR were not viable technologies for the project, as all of these would fall short on either precision/accuracy, and/or the weight of the sensor would be prohibitive for deployment as drone payload.

In addition to the challenges with precision/accuracy and weight the project application domain also involves another challenge, which has substantially influenced all aspects of the design of the entire scanning functionality (actual surface scanning, and automatic control of the drone, as described in section XXX). This other challenge is that of the turbine blades swaying in the wind while scanning, even if the turbine is parked when scanning takes place. The swaying of blades had to be taken into account at every single step in the design of the whole acquisition system. For the stereo-vision, sonar, laser-range finder and LiDAR technologies mentioned above, this blade swaying would result in very non-trivial problems with registering multiple sub-scans to each other so that they could form a bigger, coherent patch.

As a result of these considerations, it was decided that *Structure-from-Motion* would be the best scanning technology for the purposes of the project.

Structure-from-Motion (henceforth referred to as SfM) is a deceptively simple technology: 1) a set of images are taken of an object with completely normal cameras from various angles, 2) all the images are processed to locate visual features (e.g., dirt, roughness,...), 3) the visual features from every image are matched to every other image to identify features that appear in more than one image (preferable as many as possible), 4) from the matched features the cameras are calibrated and the imaging locations are estimated, and finally 5) the camera positions and image information are used to create a high-resolution 3D reconstruction of the surface.

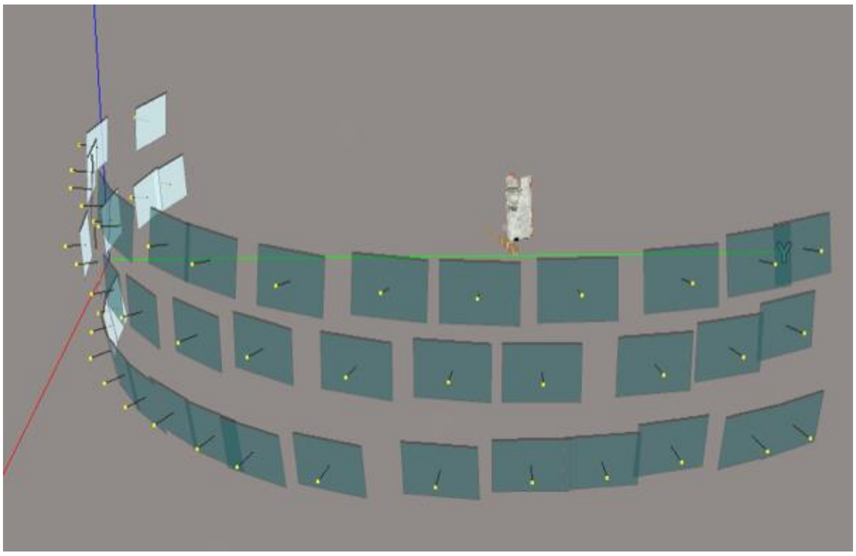


Figure: A 3D scan of a segment of turbine blade leading edge, and illustrations of the calibrated placements of all the images that went into producing the 3D reconstruction.

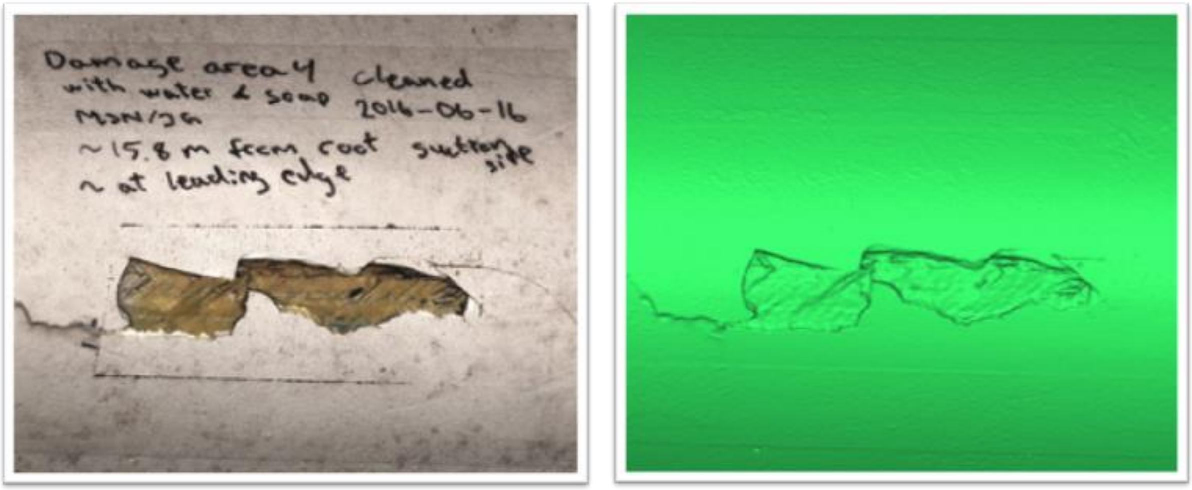


Figure: The 3D scans resulting from the SfM technology can accurately recreate very detailed surface structure, given appropriate scanning conditions.

The SfM technology “ticked all the right boxes” in terms of 1) showing promise of being able to deliver 3D scans at sub-millimeter resolution, 2) being achievable with a normal high quality camera and lens which together would be a feasible drone payload, and 3) the SfM technology is totally unaffected by blade swaying, as each necessary image can be acquired independently and the registration of the different images to each other (calibration) is inherent to the technique.

Understanding the performance of the SfM technology

Another benefit of the SfM technology is that there are numerous available commercial or free implementations of it. Throughout the project we have rigorously evaluated all relevant SfM packages.

Since the SfM technology is based on multiple images, acquired from multiple viewpoints, there are a host of imaging parameters that somehow are going to influence the quality of the final 3D reconstruction quality:

- the number of images of the surface to be scanned
- the resolution of the camera
- the field-of-view (focal length) of the lens
- the exposure and aperture settings of the camera/lens
- the distance from the camera to the surface
- how far apart the images are and how different viewing angles they represent
- amount of visual features on the surface (including how rough the surface is)
- how shiny the surface is

All these factors are *known* to influence reconstruction quality, but at the start of the project no one had really systematically evaluated these for the general case, nor even for specifically applied cases. Hence, a major effort in this part of the project went into establishing knowledge of how all these parameters influence reconstruction quality, and this work has led to several publications [1, 2, 4, 5, 6].

Extensive test regimes have been designed and carried out to evaluate how the acquisition parameters individually, and combined, affect achievable reconstruction performance. Tests have been performed on segments of real turbine blades in lab conditions, on sandpaper of various roughness in lab conditions, on blade segments in outdoor realistic conditions, etc.

Choosing optimal scanning conditions/parameters

The main purpose of mapping out the influence on all acquisition parameters on reconstruction quality was to be able to make informed choices on how to actually carry out acquisition for the blade scanning application, in order to achieve a desired level of performance in terms of accuracy and precision.

Especially towards the later stages of the project we performed tests aimed at finding reasonable compromises between on the one hand the number of images, the distance from the camera to the blade, the optical characteristics of the lens, etc., and on the other hand the resulting reconstruction quality (in order to achieve a quality high enough for being able to properly quantify the aerodynamic consequences of the roughness). An example of this can be seen in the figure below, where the same blade section is reconstructed with images from different distance to the blade and number of images.

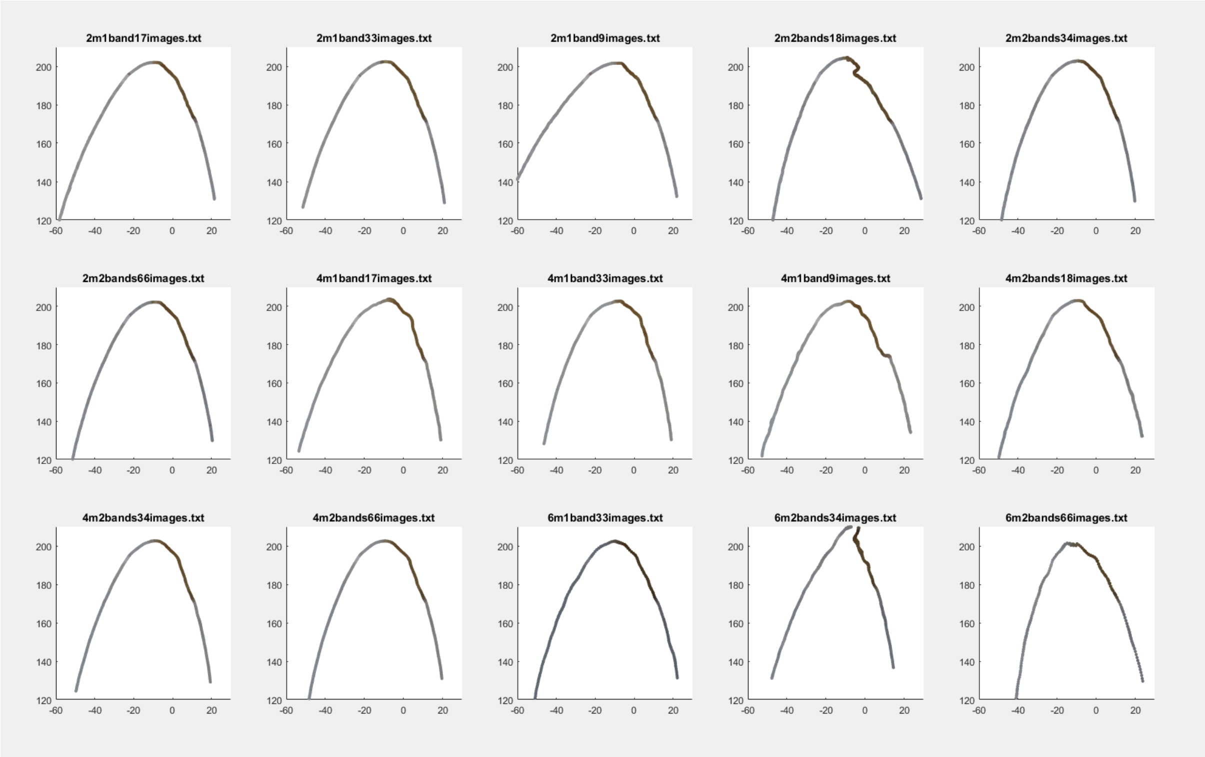


Figure: SfM results from different capturing conditions

It is of course important to note that the acquisition conditions also need to match what is practically achievable with the drone, and hence the performance of the SfM technology also heavily influenced the design of the autopilot module for the drone, as described in Section XXX.

Results:

The work documented that it is realistic that SfM can perform 3D reconstruction of leading edge patches at a resolution level of about 0.2 mm using acquisition conditions that are realistic for a drone-based acquisition system.

This level of accuracy/precision is achievable with a high-end consumer SLR camera equipped with a 2-300 mm zoom lens, at a distance of about 2 meters from the blade, using on the order to 30-50 images of each patch acquired from different viewing angles.

The SfM technique only reconstructs surfaces up to an unknown scale factor. That is, the SfM technique in itself does not provide absolute scale, only 3D. Obviously, it is necessary to determine the absolute scale of the surface roughness before it the aerodynamic consequences can be computed. The determination of absolute scale is intimately linked to parameters from the actual flying of the drone while it is performing the acquisition, and therefore the scale determination aspects are described and discussed in the section concerning the drone autopilot.

Achieved objectives – Why/Why Not:

The objectives for the scanning were: must be possible from a drone, must be able to reconstruct patches of the leading edge of turbine blades, and must achieve sub-millimeter resolution. The performed experimental evaluation demonstrated that all these objectives are met by the SfM technology.

This conclusion is based on experiments on a real turbine blade, suspended from a large gantry in an outdoor scenario, using a handheld camera from a hoist to simulate how the drone would fly to acquire the images. A complete test of the whole system with an autonomously flying drone has yet to be performed.

In the actual work plan of the project the research in the SfM technology was placed in WP1, and three milestones regarding the work were put into the workplan:

M1.1 Initial leading edge surface patch reconstruction

This milestone was fully achieved with our ability to acquire high resolution 3D reconstructions of segments of turbine blades in lab, as well as in outdoor, conditions, with acquisition performed on the ground.

M1.2 Simple surface descriptors

A study was made into what types of relevant roughness descriptors could be generated from the 3D reconstructions, and an internal report on the subject was generated [9].

Roughly mid-term in the project, it was decided by the consortium, that explicit surface descriptors would not ultimately be the way to go, as it would be too complex, and imprecise, to link those descriptors to the AEP loss. Instead it was decided to cancel the descriptor-based approach and simply match the reconstructions directly to elementary roughness cases as researched in WP3.

So, the milestone was achieved, but the work ended being slightly peripheral to the final approach chosen.

M1.3 Leading edge surface patch reconstruction, real conditions, on ground

The milestone was fully achieved, with numerous documented and quantified tests performed on various segments of real blade, with real, and with man-made erosion damages.

The performance of the 3D patch reconstruction approach has been iteratively improved through the entire project span, in response to our increased understanding of how to optimize the acquisition parameters

All in all, the SfM approach in its present state is deemed to be suitable and adequate for the purposes of the project.

For future work on the technology we made one important discovery during tests to map performance of the SfM techniques, namely that if the surface is very smooth (no roughness), then the SfM approach may start “hallucinating” some roughness (i.e. 3D noise). In fact, the more rough the surface is, the more accurate the 3D reconstruction will be, and vice versa. This is an important topic to investigate further, since it would of course be a big problem if a brand new blade is estimated to have a very rough leading edge surface. We are currently actively investigating this topic, some promising results have already been achieved, and work will continue on this topic after the completion of the project.

Dissemination:

As stated previously, the scientific work in this work package has resulted in a number of publications concerning the performance of SfM techniques in various conditions, and how the various acquisition parameters influence the reconstructions. The papers are [1, 2, 4, 5, 6].

In addition to the published scientific papers, two presentations have been given during the project period:

HUB North, Aalborg, November, 2016

The project vision and preliminary results were presented at HUB North for stakeholders of the wind turbine industry.

Metrology Day, Århus, May, 2018

The project vision and some detailed SfM results were presented for stakeholders in the area of metrology.

The results from this work has also led to invitations into other research project proposals, and will continue to inform scientific work in this area.

5.2.2 Development of Drone-Based Image Capture (AAU):

Objectives:

- Structure from motion is powerful tool for scanning both indoor and outdoor environments, but as any computer vision based technology, it comes with a number of prerequisites for success use. Some of the most important ones are:
- For a surface to be reconstructed enough photos needs need to be taken, so each part of it can be seen;
- The taken photos need to be from diverse angles and directions;
- The resolution of the captured surface in the photos needs to be high enough - so both a high resolution camera needs to be used and the photos need to be taken close enough to the surface.

Based on the findings on the requirements for getting high precision SfM reconstructions, it is determined that using a drone for capturing the necessary images is necessary. In addition the drone flight needs to be autonomous, because of the maky risks flying so close to the wind turbine blades and the need for reproducible results. A drone pilot being present only to look at the captured data and intervene in the possibility of catastrophic failure.

Going from these findings a number of objectives were set up:

- Setup an autonomous drone platform, containing all the necessary cameras, sensors and communication
- Develop a localization and self-positioning algorithms for enabling the scanning process
- Develop a ground station platform for monitoring the scanning process
- Use all captured data to position, scale and clear the noise from the reconstructed blade segments

Main activities:

Autonomous drone platform

To achieve this objective a number of drone platforms were researched. For a platform to be chosen, it needed to satisfy a requirements:

- To have enough battery life to scan at least one blade.
- To be able to carry all the necessary camera, sensor and communication equipment
- To be resistant to wind gusts and to have GPS self positioning/hovering
- To be able to transmit images to the pilot

To be able to achieve semi- or full autonomous flight if necessary.

This was the objective that required the most changes in the project’s development. When work started in 2015, there were no commercial platforms that were able to satisfy all the requirements. This meant that the drone platform needed to be built from scratch, using open source technology.

Two open source drone platforms were selected - an Iris+ small testing drone for training and developing the communication and movement algorithms and a DJI S1000 large payload drone for the development platform for the necessary sensors and at the time final platform. Because of the open source nature of the platform, the movement, communication, the data gathering needed to be made from scratch as well. Images of the two drones can be seen in the figure below.

Figure: The Iris+ small drone with the LiDAR attached to it (left) and the DJI S1000 drone with the camera and gimbal attached

After a number of tests it was determined that the initially selected DJI S1000 drone was not stable enough for the planned precision flying, as well as it did not provide an easy way for the pilot to take control back from the autonomous mode. This meant that another platform needed to selected. At the time another drone solution was introduced by DJI for commercial drone flight - the Matrice 600 (as seen on the figure below). The platform was selected as it provided more stability, a built-in testing environment and an official SDK for programming the drone and connecting to the internal and external sensors.

Figure: The DJI Matrice 600 drone, in a test flight

As part of the development of the platform it was decided that because of the distance the drone needs to operate from the pilot, all of the algorithms for self-positioning, movement, sensing, scanning needed to be done on a on-board computer. Initially the Nvidia Jetson TX1, was chosen, but because of the size of it and some problems with development on it, it was discarded in favour of the less powerful, but easier to use Raspberry Pi 3. All the algorithms were rewritten for more optimized execution. Initially all algorithms were written for testing through Matlab and once the onboard platform was deemed necessary everything was ported to Python. Finally when the drone was changed to the closed platform DJI Matrice 600, the code was ported again to C++ for a native execution using the provided DJI SDK.

Localization and self-positioning

An initial research into positioning and localization algorithms was conducted, looking into their complexity, precision, robustness, etc. Because of the nature of the scanned blade surface it was impossible to use purely computer vision positioning algorithms. Another complicating factor were the oscillating movements of the blade, because of the wind. Finally the algorithms needed to be lightweight enough to be run in real time on the onboard system. These factors required the development of a custom localization and positioning system, which was not fully dependant on GPS world coordinates, but placed the drone's position compared to the blade at any given moment [3]. In addition as a sensor for this, the LiDAR was chosen. This algorithm went through many iterations through the development of the project, making it more robust adding filtering, self-correction, emergency stopping, scanned surface following, etc.

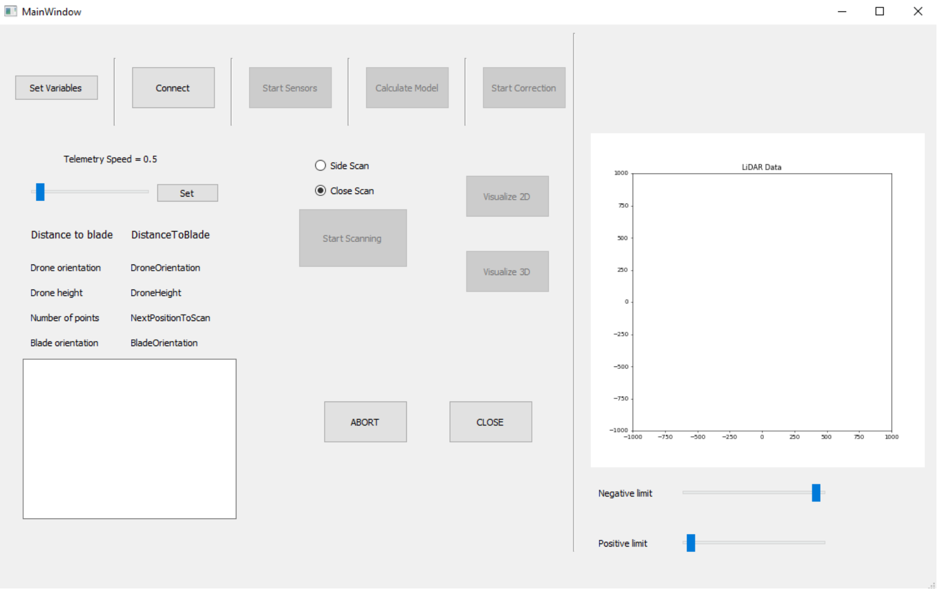
At first a low cost, easy to use rpLiDAR was chosen as the main sensor for development. It provided precise results, but it was proven to not be robust in the presence of direct sunlight. Two different solutions were tested - the cheaper, but more robust Scanse Sweep and the more expensive, but more robust and precise Hokuyo UTM-30LX. The three LiDAR solutions are shown in the image below.

Figure: All the tested LiDAR solutions - from left to right - the rpLiDAR, Scanse Sweep and Hokuyo UTM-30LX

Ground station platform

Together with the drone platform, the development of the pilot assistive software on the ground was developed. This was necessary because the autonomous nature of the platform - the pilot needed to be able to always follow and react to the drone, while another person positioned on a ground station computer needed to look at the captured data transmitted from the drone.

For connecting to the ground station a combination between DJI's proprietary communication system and a custom made Xbee based system was developed. A prototype of the graphical user interface for initializing communication with the drone, sending commands and receiving and visualization of data was developed. The interface can be seen below.



Telemetry Speed = 0.5

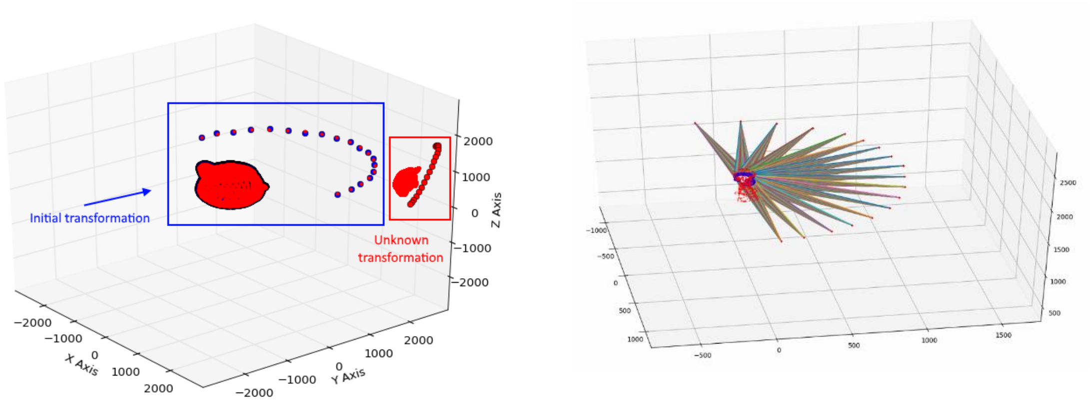
Distance to blade DistanceToBlade
Drone orientation DroneOrientation
Drone height DroneHeight
Number of points NextPositionToScan
Blade orientation BladeOrientation

Figure: View from the graphical user interface for the ground station prototype

Position, scale and clear noise

Because of the nature of SfM, the real world scale of the reconstructed surface cannot be determined only from the captured image data. This is why a number of algorithms were developed to scale the reconstructed surfaces using either the camera's real life position estimation [1], when the photo was taken or using the captured LiDAR data [6]. Visuals from both methods can be seen in the figure below. Because of the noisy and changing capturing environment these algorithms could also estimate the uncertainty of the scaling, as capturing the roughness and damages as precisely as possible is one of the main requirements of the project.

Initial work was done for positioning the reconstructions depending on the height of the blade and their orientation, using data from drone sensors.



a)

b)

Figure: Visualization of the two scaling algorithms - a) demonstrates finding the transformation and scaling using positioning data, while b) uses the distances measured by a LiDAR

<u>Results</u>:

The results from the set up objectives are summarized below.

- A number of drone platforms were developed and tested, with a final commercial platform chosen. A on-board system was chosen and the communication between the drone flight controller and it was developed. Automatic image and environment reading capture was set up.
- Sensors for self-positioning were chosen and algorithms were developed for robust, lightweight and precise autonomous drone movement and obstacle detection [3]. The self-positioning was tested in a simulated environment and in laboratory conditions, with initial test in an outdoor environment conducted.
- A prototype ground station system was developed with communication between the on-board ground computers. A prototype graphical user interface was created for scan initialization, data visualization, command receiving and sending.
- Algorithms for using drone captured data for scaling, positioning and noise reduction of the reconstructed data were developed [1], [6].

<u>Achieved objectives – Why/Why Not</u>:

The final drone platform was developed iteratively and went through a number of changes through the life of the project. The initial plan of having a ready made drone platform was proved feasible because of the then current drone technology. This made it necessary to create a drone platform from scratch using open source technology. This also was proved impractical, which led to the final drone platform, which uses commercial out of the box parts and an integrated software development kit, but with added custom solution sensors and algorithms.

The self-positioning and localization algorithms for drone movement and obstacle detection were iteratively developed and tested both in a simulated environment, as well as in a laboratory conditions, with initial outdoor tests.

The communication between the ground station, the onboard computer and drone controller were developed and tested in laboratory conditions. The data transfer speeds, latency and robustness to communication breaking was also tested. An initial prototype of the ground station interface was developed.

Finally a number of algorithms for post-processing the 3D reconstructions were developed based on the captured sensor data.

The main reasons for not being able to progress more in the given timeframe were underestimating the needed resources both timewise, manpower wise and environment wise, the state of the technology at the time of the project and how it evolved in the three years and finally unforeseen problems connected to testing the platform.

The allocated time for developing the drone platform and the autonomous flight algorithms was underestimated and even with adding more time and more resources was not enough. This combined with the lack of easily accessible testing environments for the flights - both indoor and outdoor, made the main slowdown of the project.

The iterative development nature of both the platform used and the sensors meant that a lot of work needed to be done to port and redo already done work. This was caused by the state of the drone technology, which changed rapidly - with the initial selected systems getting deprecated and new commercial systems becoming available for purchase.

Finally, an unforeseen drone crash and the resulting damage to the drone, sensors and camera set the project at least six months back, as it meant long waiting times for the repairs, the shipping of the gear, the fixing of documentation for insurance, etc.

As most of the parts of the autonomous drone platform are developed, it is estimated that approximately 1 manyear is needed to get them combined into a final system with full functionality and to extensively test it.

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In the actual work plan of the project the research in drone control was placed in WP1, and three milestones regarding the work were put into the workplan:

M1.4 acquisition with manually controlled drone

This milestone was achieved, as we performed this on a few occasions of varying complexity (foam blade model mounted on pole, real blade suspended from large gantry, real blade on real turbine). In none of the cases the leading edge reconstruction was actually of high enough quality for the purposes of the project, due to the fact that a human drone operator is not capable of flying close enough to the blade, hence underlining the need for the autopilot technology developed in the project.

M1.5 Initial tests of autopilot system for acquisition

This milestone was achieved. Late summer 2018 the consortium was ready to perform these tests using a turbine blade mounted in a gantry at PowerCurve. A number of tests were performed, but due to the firmware of the drone (not the consortium’s software, but the software from the drone manufacturer) not fully supporting the promised GPS functionality, the drone ended up crashing; a crash it took the consortium many months to recover from in terms of piecing a fully functional drone back together.

M1.6 Complete implementation of drone-based acquisition

The milestone was not fully achieved. All building blocks that go into this system are developed and have been tested individually, but a complete integration test of the entire system has not been possible due to all the described practical challenges with establishing the suitable technology for the autopilot on the drone. As described above we initially meant to purchase a commercial drone, but discarded that approach as commercial drones, at the time, did not allow for control from 3rd party software and sensors (our control software and LiDAR sensor). Then we decided to build our own drone from available state-of-the-art individual components, but once this drone was completed, we had to realize that it was not airworthy enough for the purposes of the project, and as a software platform for control it did not provide sufficient functionality. Since a couple of years had now passed, and since development in drone tech at this point was advancing incredibly fast, we in early 2018 then looked one more time at commercial drones, and found that we could now purchase a commercial professional platform with all the required basic functionality (except autopilot which we developed ourselves). This proved to be a viable approach, and we were very close to a full demonstration test when the drone crashed.

The complexity of developing the drone autopilot functionality was underestimated in the original work plan. Luckily we saw this problem very early on in the project, and allocated significantly more resources (person months) into this relative to the original plan. PowerCurve has thrown approx. 1000 person hours into this, and AAU have spent nearly 2000 person hours more than planned on the activity (which was possible be re-allocating funds from travel and equipment, and by AAU having lower expenditures per person hour than originally budgettet).

In conclusion, establishing the drone autopilot is absolutely essential for performing scans of sufficient quality. Manual drone control is possible. The level of performance required by the autopilot functionality to achieve this is at the very edge of what is possible with current technology, and in retrospect we have to admit that our requirements have been slightly ahead of the technology. Nevertheless, we remain absolutely confident that the required functionality is achievable. As most of the parts of the autonomous drone platform are developed, it is estimated that approximately 1 person year is needed to get them combined into a final system with full functionality, and to extensively test it.

During the process of developing the autopilot we also developed some really good techniques for locating the drone in blade-centric coordinates, which is essential for handling swaying blades, and we developed the entire framework for calculating the true scale of the 3D reconstructions.

Dissemination:

A number of conferences were attended to disseminate the findings from the project. The conferences were chosen to represent the best outlet for showing the complex nature of the project - a combination of computer graphics, computer vision and robotics. The time for each conference was chosen so that all the needed data was gathered and all the tests were made. The need for simulation, laboratory and real world test results meant that dissemination at conferences could be done at a slower rate.

In addition to the scientific articles, one presentation has been given of the drone system for the IT Days 2018 in Aalborg University.

Published Papers

[1] Performance Characterization of Absolute Scale Computation for 3D Structure from Motion Reconstruction

Date: 2019

Conference: 14th International Conference on Computer Vision Theory and Applications

Authors: Ivan A Nikolov, Claus B Madsen

[2] Interactive Environment for Testing SfM Image Capture Configurations

Date: 2019

Conference: 14th International Conference on Computer Vision Theory and Applications

Authors: Ivan A Nikolov, Claus B Madsen

[3] LiDAR-based 2D Localization and Mapping System using Elliptical Distance Correction Models for UAV Wind Turbine Blade Inspection

Date: 2017

Conference: 12th International Conference on Computer Vision Theory and Applications

Authors: Ivan A Nikolov, Claus B Madsen

[4] Benchmarking Close-range Structure from Motion 3D Reconstruction Software Under Varying Capturing Conditions

Date: 2016

Conference: Euro-Mediterranean Conference

Authors: Ivan A Nikolov, Claus B Madsen

[5]Inside-Outside Model Viewing: A Low-cost Hybrid Approach to Visualization and Demonstration of 3D Models

Date: 2016

Conference: 11th Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications

Authors: Ivan A Nikolov

Papers in Review

[6] Absolute Scale Calculation for Structure from Motion Reconstructions using LiDAR Measurements

Date: 201?

Conference: British Machine Vision Conference

Authors: Ivan A Nikolov, Claus B Madsen

Papers in Progress

[7] Verifying the accuracy of roughness detection using SfM on wind turbine blades,

through metrology ground truth comparison

Date: 20??

Journal: Sensors

Authors: Mikkel Nielsen, Ivan A Nikolov, Emil Krog Kruse, Claus B Madsen, Jørgen Garnæs

[8] Predicting Noise on 3D Reconstructions using SfM

Date: 2019

Conference: ??

Authors: Ivan A Nikolov, Claus B Madsen

Internal reports

[9] Quantitative description of surface roughness and shape for LER project, Mikkel Schou Nielsen, DFM, sent 2016-03-04, DFM DOC 15 505

[10] AAU 3D report final version- https://docs.google.com/document/d/1PFK0IHrhxSCYmbSbVvNJseqduc0Tkpz8JGEYlkuKN40/edit?usp=sharing - This is the main document that compiled from parts of what has been researched in these years - it contains overviews of experiments in Risø and on the small wind turbine chunk, technical specs of the first and second drone system, reconstruction tests, LiDAR test, synthetic data creation, etc.

[11] SfM LER pipeline documentation- https://docs.google.com/document/d/1hEDMXSB5XlJWWi6QvyrcJNVolv4BjKHIJNJ2jeOFq7c/edit?usp=sharing - This is the overview of the pipeline that we ended up with for going from images and positions to a sliced model

[12] SfM reconstruction tips- https://docs.google.com/document/d/1gcEd6_QIldo8CQirA0NsouweTBF7l1oOdiI0lUyKPI4/edit?usp=sharing - This is a short documentation on good practices and tips in gathering images and reconstructing.

[13] Vertical image acquisition - https://docs.google.com/document/d/121seBr9vJQE9nfo7nDyPf7Vj_Ejsdcs_i5wv-xKU72s/edit?usp=sharing - overview and thoughts on the vertical image acquisition that we did in the beginning on 2019

[14] First drone flight test- https://docs.google.com/document/d/1c5gaslicaF0L2IksNr8llkn4Oc2pN3AQvwGF0jgsIwA/edit?usp=sharing - overview of the first test flight with the old DJI S1000 demonstrating some of the problems that led to changing of the platforms

[15] Vattenfall visit to AAU and scanning - https://docs.google.com/document/d/1zpLd_nApRx9LB5LROmgly_WV-kHqn1atBUG3dW_G2_Q/edit?usp=sharing - very short document outlining the visit of Vattenfall to AAU in 2017 and their scanning of the wind turbine blade.

5.3 WP2 - Validation of SfM (DFM):

Objectives:

Ordinary 2D images have been used to examine wind turbine blade for some years. This project focus on a new idea, that is, to use SfM acquired from cameras on drones to measure and reconstructed the "true" 3D shape of the wind turbine blades surface with an accuracy better than 1 mm. The 3D shape shall be used to improve the estimate of the performance of the wind turbine blades via aerodynamical measurements and simulations using the 3D shape and ultimately give quantitative decision tool for turbine owners O&M plans. However, if the SfM method has to be used, in particular by turbine owners, it is very important that the reliability is proven. This is done by validation of the SfM method, and involve acquiring evidence that the SfM method is fit for purpose.

We expected to get some estimation of resolution of the SfM method and some assessment of limitations to the accuracy.

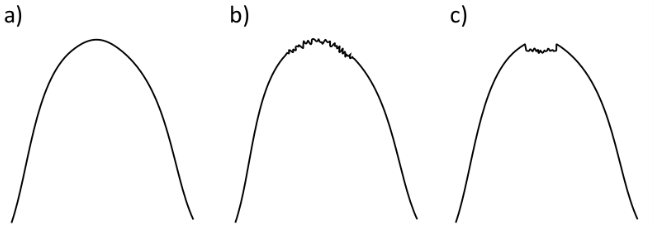

Figure: Three leading edge (LE) surface profiles of different roughness morphology. a) Smooth surface LE. b) Rough surface on LE. c) left in LE with internal roughness.

Main activities:

Input to M1.2 *Ability to automatically produce simple surface descriptors, e.g., RMS roughness* **Input given**. **Report per Apr 7th 2016**

Summary: To set a basis for the assessment of the surface roughness a report was made to clarifying the nomenclature and different kind of leading edge (LE) surface profiles of different roughness morphology. Details are given in [16]

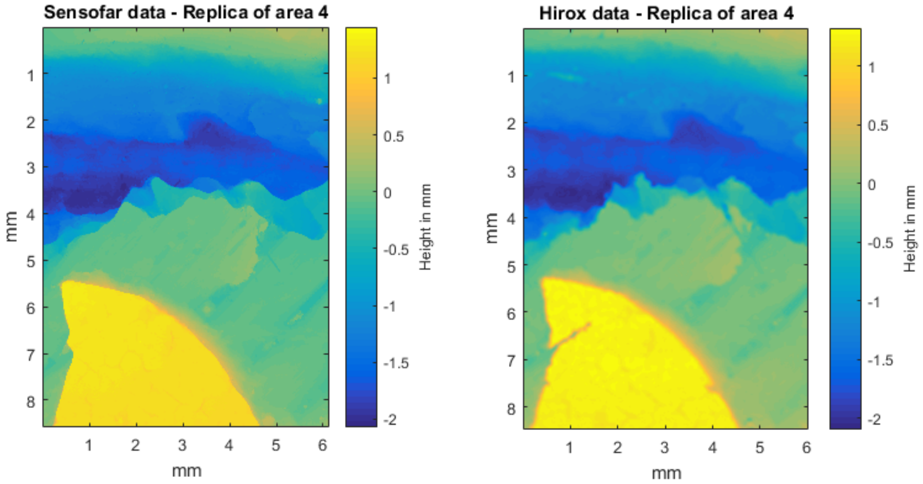

Figure: Height map of replica of wind turbine blade (inverted and mirrored). Left: Confocal microscopy. Right: 'Depth-from-focus' microscopy.

M2.1 *The microscope build is validated with a comparison to DFM‟s traceable confocal microscope* DFM lead, completed. Report per Jan 16th 2017.

Summary: Optical microscope systems can provide a traceable and quantitative measurement of a wind turbine blade either directly for smaller pieces or indirectly from replica of the surface. Two microscopy techniques are depth-from-focus and confocal microscopy. *In the project the performance of the former compared to the more well-established confocal microscopys is assessed.* Detailed activities are described in [17]

M2.2 *Measurement report on the reference artefact fabricated in D2.2.* DFM lead, completed. DFM report DFM-2017-F09 per Jun 29th 2017.

Summary: In order to provide a “ground truth” for the drone-based system in the project, the surface topography of wind turbine blades must be measured. However, for installed turbines a direct measurement is not feasible. Instead, replica of the surface can be made using polymer replication material[1] for later measurements in the laboratory. In order to use this technique, the accuracy of the replicated *heights* of the topography must be as good as the spatial resolution of the lab measurements. In the project the replication technique is evaluated by comparing microscopy measurements of master and replica using two reference objects. Detailed activities are described in [18]

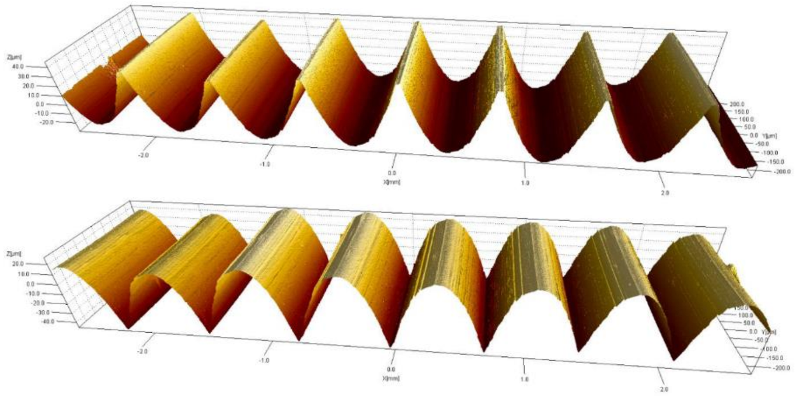

Figure: 3D visualization of roughness standard from confocal microscopy. Scans of master (top) and replica (bottom) with a nominal roughness of 12.5 µm

M2.3 *Investigation of the replication techniques on microstructures* DFM lead, completed. DFM report DFM-2017-F08 per Jun 29th 2017.

Summary: In order to use the replication method, the accuracy of the replicated heights of the topography must be as good as the spatial resolution of the lab measurements. In the report, the performance of the replication technique is evaluated by comparing microscopy measurements of master and replica using two reference objects. Detailed activities are described in [19]

M2.4 *Measurements on 5 segments of wind turbine blades* DFM lead, completed. Report per Nov 24th 2017

Summary: Blade originated from decommissioned Vindeby wind farm. Six regions-of-interest areas on leading edge selected for inspection. Detailed activities are described in [20]

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[1] The replication method is a method where a thin polymer film non-destructively replicates the microstructure

M4.2 Transportable microscope used in the field 32. DFM not lead, completed. Results presented on meeting 2019-01-10 DFM memo/presentation DFM DOC 16 933

Summary: In agreement with the decision on a steering group meeting the milestone was adjusted so the field test was focused on replication as it was agreed that this would be more reliable. Uptower replication was done and comparisons to AAU photogrammetry have been conducted. Detailed activities are described in [21]

Results:

The comparison of depth-from-focus and confocal microscopy (**M2.1)** resulted in a relative root-mean-squared deviation (= "error") in the range of 2-5% for size scales in the range from 10 µm to 8 mm lateral and vertical from 25 µm to 2 mm. The absolute root-mean-squared deviation (= "error") was up to 90 µm Overall, the depth-from-focus microscopy can be used as an alternative to confocal microscopy for the larger millimeter size structures in the LER project.

The two types of artefacts investigated (**M2.2**) highlighted different properties of the SfM measurements. By use of the artefacts, the AAU SfM method could be compared quantitatively to the the DFM microscopy techniques. The results highlight some important challenges for the SfM method when going forward. The results are further described in a draft manuscript [22]

The replication method (**M2.3**) was found to produce quantitatively reliable and reproducible results. For the LER project, the level of accuracy and precision are well within the scale of 100 µm that the fotogrammetry measurements aim for.

The inspected areas of the Vindeby turbine (**M2.4**) blade illustrate a wide range of morphology of eroded features. Max depth of eroded areas ranged from a few tenths of a mm to a few mm (0,2 mm – 2,6 mm).

In summary the validation of the SfM method gave some limits for the measurement capability for a very high resolution, close range SfM for a particular focal length. First of all, many factors can limit the measurement capability including a featureless surface without shadows. On a uniform model surface of sandpaper, a resolution in the order of 0.5 mm could describe many of the results. For an ideal surface of well-defined steps with additional colored texture features the vertical resolution was down to the order of 1 %. Another rough way of summarizing the findings is that the resolution – for the high end system studied – is in the order of 15 pixels. Under real measurement conditions the uncertainty must be assessed individual and will be higher.

Achieved objectives – Why/Why Not:

A useful assessment and validation of the SfM were achieved, a basis for the roughness description was developed and filed test of the method were done. The DFM objective were achieved in the sense that all the DFM lead milestones (**M2.1** – **M2.4**) were achieved.

Dissemination:

Talk: Surface roughness measured by different instrument - how can it be best used? Surface Characterization Conference, Danish Technological Institute, arranged by ATV-SEMAPP.dk and Danish Technological Institute, J. Garnæs, Co-authors on presentation: S. R. Johannsen, P. E. Hansen, J. S. Madsen, M. S. Nielsen and G. Zeng, 5-6 March (2018) – LER example included

In Danish: Case i analyse udgivet af GTS-foreningen: GTS-foreningen: Hæfte og online "Den teknologiske videnbro – nu og i fremtiden"2017-09-01 **Droner og 3D-fotos dokumenterer vindmøllevingers tilstand** https://gts-net.dk/wp-content/uploads/2017/09/Den-teknologiske-videnbro-nu-og-i-fremtiden.pdf

In Danish: Jern-Maskinindustrien 2018-01-12 JG Overflademålinger **Klarhed kræver instrumenter**, Nye tekniker og nye instrumenter til måling og karakteristik af overflader stormer frem i industrien, Arkiveret: DFMDOC 16461

DFM has described and published on DFMs homepage a product sheet with a description of the replication methods [23].

Talk: Mikkel Schou Nielsen, "Measuring leading edge roughness using Structure-from-motion photogrammetry", Third network meeting in the Failure Analysis, Characterisation & Testing group. 2018-11-01 DFM, Hørsholm

Talk in Danish: Hvad er sporbarhed? Hvad skal vi bruge den til? Og hvordan opnås den? Søren Kynde, FVM-temadag 2019-01-31 DFM, Hørsholm – LER example included

The reports and papers listed below are enclosed except – to avoid confusion - item number **Error! Bookmark not defined.** *The influence of surface texture on Structure* which is already included in the material send by Claus

[16] *Quantitative description of surface roughness and shape for LER project*, Mikkel Schou Nielsen, DFM, send 2016-03-04 DFM DOC 15 505

[17] *Comparison of depth-from-focus and confocal microscopy*, Mikkel Schou Nielsen, DFM

[18] *Measurement report on step-height artefact and sandpaper LER project milestone M2.2*, Mikkel Schou Nielsen, DFM

[19] *Investigating the performance in replication of height structures*, Mikkel Schou Nielsen, DFM

[20] *LER milestone M2.4 – LE surface topography on Vindeby turbine blade*, Mikkel Schou Nielsen og Jørgen Garnæs, DFM

[21] *WP2 and DFM milestones*, Mikkel Schou Nielsen et al. DFM, send 2019-01-15

[22] *The influence of surface texture on Structure-from-Motion reconstructions*, Mikkel Schou Nielsen,∗, Ivan Nikolov, Emil Krog Kruse, Jørgen Garnæs, Claus Madsen To be resubmitted to the Journal Sensors.

[23] https://dfm.dk/wp-content/uploads/2019/03/Produktblad_Replikering_DK_2017-11-06.pdf

5.4 WP3 - Predicting the aerodynamic performance and influence on annual energy production from roughness

5.4.1 Fast and efficient aerodynamic predictions of blade sections (DTU)

M3.1: Modelling of roughness in flow solvers

Objectives:

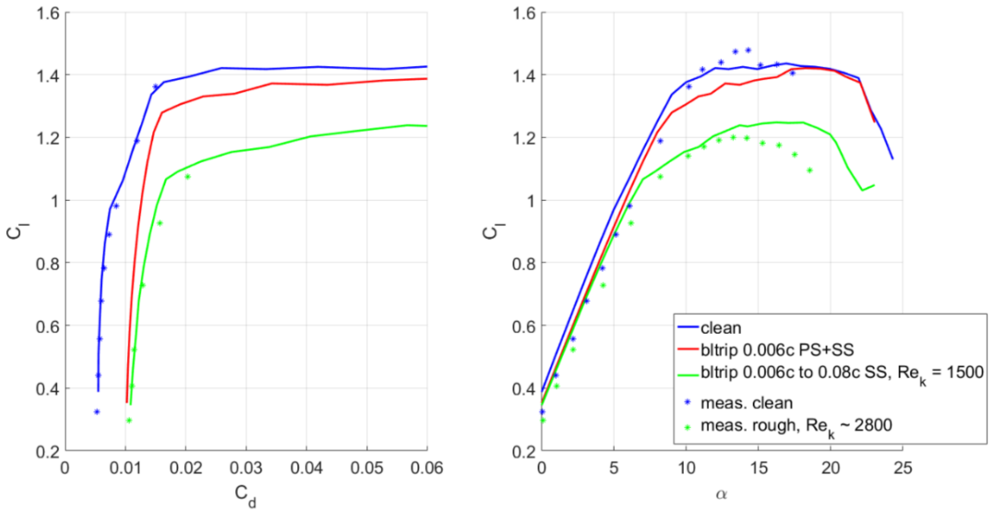
Even though the loss in performance of wind turbines ultimately should be predicted and tested on full-scale wind turbines, the stochastic nature of the wind and the fact that wind turbines often are erected in remote areas will lead to complex, time consuming and expensive tests. Furthermore, results from predictions of the aerodynamic rotor performance can also be challenging to interpret. Therefore, investigations of prediction tools for blade sections from wind turbine blades were carried out. When predicting the performance of blade sections different computational tools can be used. The aim of this part of the project was to develop a prediction model that in a fast and efficient way could predict the performance of blade sections with leading edge roughness (LER).

Main activities:

To be able to model the performance in a fast and efficient way a model for surface roughness was investigated for panel codes like the DTU developed code Q^3UIC or the well known XFOIL. The panel code XFOIL developed by MIT for the use for blade sections for gliders and airplanes has been validated and has been used for 20 years and more. However, the possibility to predict the aerodynamic performance assuming non-ideal surface conditions is not part of the panel code, but with the conditions for wind turbine blades this will be a very valuable feature. Thus, a sub model for the code and an implementation of this was carried out.

Results:

The prediction tool XFOIL, including a new sub model, was in its early stage presented at the research conference WESC 2017[24]. The sub model is promising and show good performance in terms of prediction of forces. The most promising is the good correspondence between the increase in drag and the loss in maximum lift that is observed when using the model – see the figure below.



This is in contrast to other models for LER where the loss in drag is underestimated, whereas the maximum lift shows the right loss – or opposite. However, the numerical stability of the code is not resolved, so even though some airfoils or some angles of attack can be predicted there are other airfoils or angles of attack that might fail in contrast to the original XFOIL code that is rather numerical stable.

Achieved objectives – Why/Why Not:

The sub model simulating LER worked well on some blade sections. However, in the test of the model on other blade sections to validate the code it turned out that the code was not as stable as desired. This issue was not resolved before the end of the project and this has to be investigated and made more stable in the future. Even though the potential of having a code that worked was big, there was not resources to continue the development of the code, because the work of stabilizing the numerical simulations potentially can be very time consuming. However, in the future stabilizing the code will be investigated further.

Dissemination:

The reference [25] concerns a conference where the roughness model was presented. This was important to discuss the modeling with other researchers in the area. The conference was in Copenhagen at DTU 28 June 2017.

M3.2: Prediction aerodynamic performance with leading edge roughness

Objectives:

Wing sections with selected surface roughness types will be tested in the new national wind tunnel to investigate the influence from roughness on the aerodynamic performance and to validate the predictions carried out with Computational Fluid Dynamics and other methods. Application of the different types of roughness and different types of vortex generators on the wind tunnel model will be investigated.

Main activities:

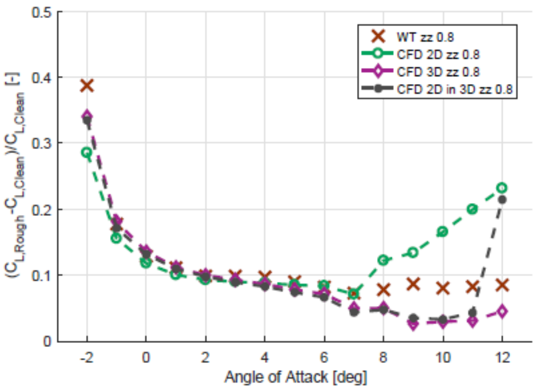
A vast amount of work has been put into this task. The majority of the PhD work has been on this subject as well as 4 scientific articles by the PhD from DTU. The main activities has been on developing and testing a good method for simulating the influence of different kinds of LER. Wind tunnel experiments from earlier project has been used as a basis for simulations. Simulation of very small LER was a challenging task in CFD. The CFD mesh must fulfil a series of constraints in order to converge and give useful results as well. A mathematical roughness model was implemented in CFD as well, in hopes of reduced constraints to the mesh.

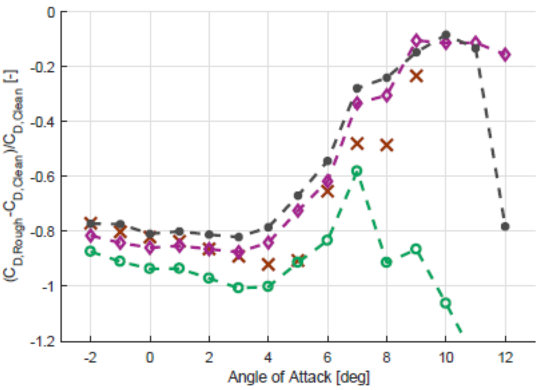
To short it down: One method changes the mesh whereas the other method changes the flow solver.

Results:

The method with changing the mesh is useful when LER has a certain magnitude or so called "steps". This could be zigzag tape, which is a tape used to put on airfoils in wind tunnels, to emulate LER. The zigzag tape does not have any roughness itself, it mainly serves as a method for disturbing the airflow.

Below is a figure where simulations are compared to wind tunnel measurements for a zigzag tape with a height of 0.8 mm. The airfoil, NACA63418, is 18% thick and 600 mm long.





The left figure shows the airfoil with LER's ability to produce lift compared to the clean airfoil. A value of 0 means that it is unchanged compared to the clean airfoil. A value of 0.1 means that the lift is reduced by 10%. A good correspondence can be seen between wind tunnel tests and different kinds of CFD simulation (2D, 3D and pseudo-3D). On the right side, the drag can be seen. A value of -1 means that the drag is 100% higher on the LER airfoil compared to the clean airfoil, i.e. the drag has doubled. Again, the purpose of the figure is to show that it can be simulated with a good agreement.

The other method, changes in the flow solver, is used to simulate distributed roughness suck as erosion, emulated by using sandpaper on the leading edge of the same airfoil. The results can not be shown as the article is under progress and submitted within one month, where it must be new. The governing result is that the current method for simulating the airflow on and airfoil with a distributed rough surface might need improvement.

Achieved objectives – Why/Why Not:

The objective was achieved for simulating larger scale roughness whereas improvements are needed for simulating distributed roughness. More wind tunnel experiments are needed in order to calibrate the models.

Dissemination:

The work resulted in 4 articles where 3 is still in the writing or reviewing process. They will all be submitted before the 30th August which is the PhD deadline.

One article [26] has been published:

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[26] Krog Kruse E, Sørensen N and Bak C 2018 Predicting the Influence of Surface Protuberance on the Aerodynamic Characteristics of a NACA 633-418 (Journal of Physics: Conference Series (Online))

5.4.2 *Wind tunnel tests (DTU)*

M3.3: Wind tunnel tests on airfoils with different categories of roughness

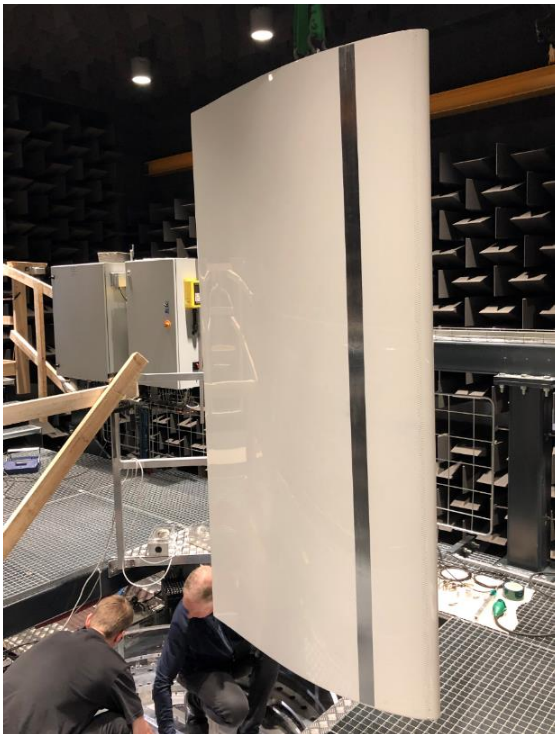
Objectives:

The prediction of performance of blade sections needs to be validated. This can be done by carrying out wind tunnel tests. Based on such tests, aerodynamic characteristics with different kinds of surface damages were mapped. In this way, an overview of the severity of damages can be mapped. The aim was to create the basis to form a transfer function from surface conditions on the blades to the annual energy production from wind turbines.

Main activities:

As part of the wind tunnel tests it was decided which configurations of the blade sections that should be carried out. Therefore, it was important to map which damages that are appearing on real wind turbine blades. Based on these damages a well-known airfoil NACA 63_3-418 was manufactured that had an exchangeable leading edge so that different types of damages could be tested. This airfoil was in different configurations tested in the new Poul la Cour Tunnel established at DTU Risø Campus and inaugurated in 2018. A challenge in the project has been the finalization of the Poul la Cour Tunnel that was expected to be finalized much earlier than was the case. This led to a postponement of the finalization of the project and the wind tunnel tests were carried out very late in the project. It was considered to move the wind tunnel tests to another wind tunnel, but reservations of tests in good wind tunnels have to be made at least one year in advance so this was not considered as a good choice.

Below pictures are from the Poul la Cour wind tunnel:

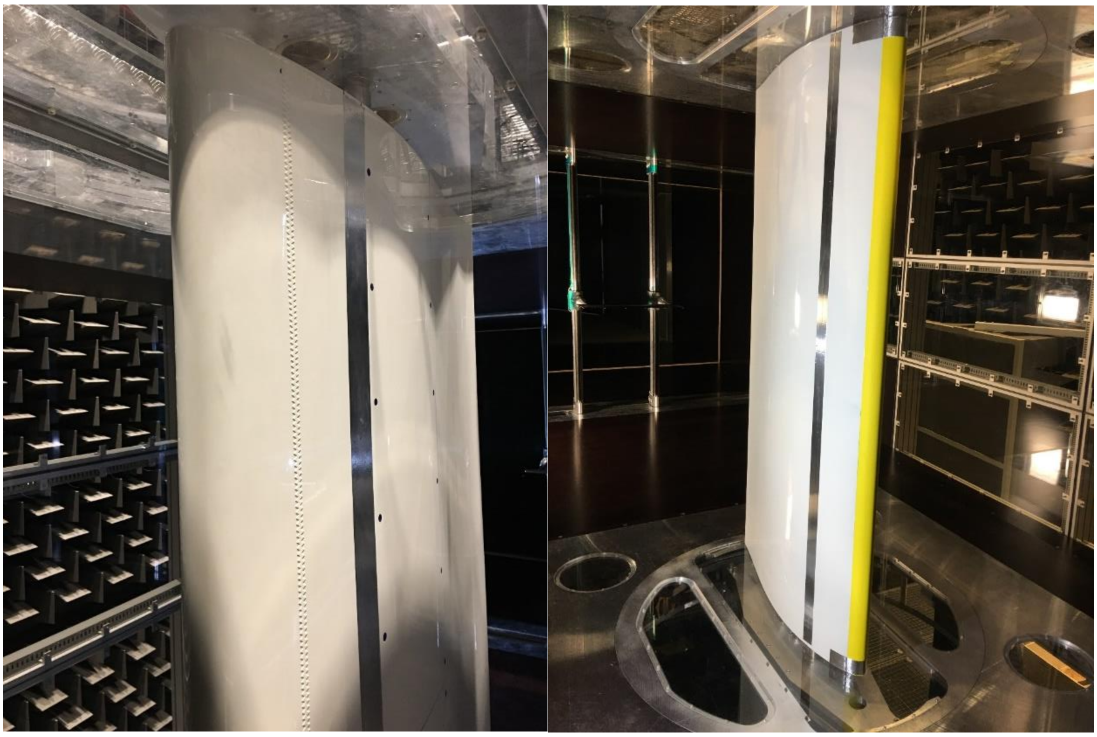


Results:

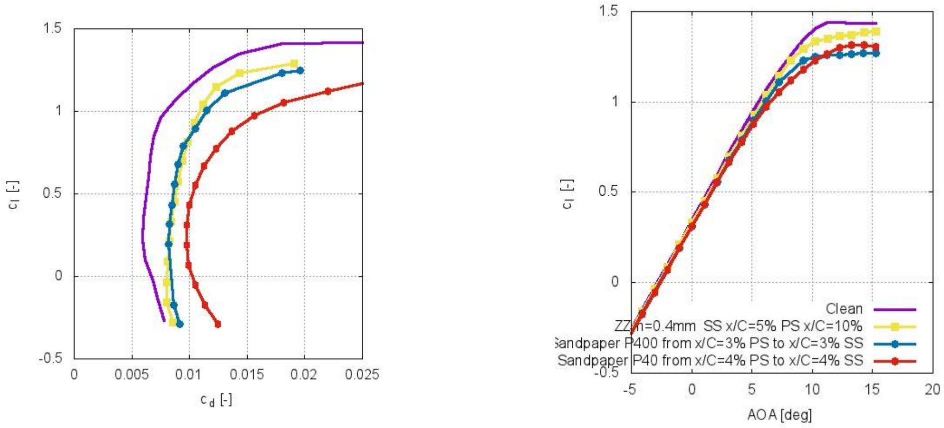
Inspections on wind turbine blades are frequently made by wind turbine owners. Such inspection reports were shared with the consortium and these reports were very important to get an overview of which damages that should be expected. Below three photos from inspection reports are shown. These photos represent three typical types of damages: 1) The sandpaper type of damage at the leading edge, 2) the cavity type of damage at the leading edge and 3) the cavity type of damage a fraction of the blade width downstream of the leading edge. Based on this analysis the setup of the airfoil for the wind tunnel tests were determined.

However, before the wind tunnel tests were carried out and in an early stage of the project, basic work was carried out to understand how sensitive the aerodynamics is to surface imperfections[27]. With this work, it was communicated to the industry and the rest of the consortium, which sizes of surface imperfections we were looking for when blade surfaces are degrading. Also, a limited number of wind tunnel tests carried out in another project were analyzed to understand how LER influenced the aerodynamic performance and how this degradation of the aerodynamics could be compensated by the use of vortex generators (VGs)[28]. It was clear that the loss of lift on the blade can be compensated, but the lift-drag ratio cannot be compensated to the same extend. It was also clear that the position of the VGs was dependent on the height of the VGs.

The latest results from the wind tunnel tests in the project were presented at the wind energy research conference WESC 2019 where very interesting results were highlighted. A lot more results was part of the project, but since wind turbine owners and wind turbine manufacturers use a traditional way of testing LER and these tests seems not to represent real LER on wind turbines these results were of prime interest for the audience[29]. These measurements show among other things that the use of zigzag tape at the leading edge of blades to simulate roughness can create the same drag increase as when sandpaper – that is closer to reality - is used. The airfoil mounted in the test section is shown below with zigzag tape (left) and sandpaper (right).



However, the penalty in maximum lift is somewhat bigger with sandpaper and therefore, zigzag tape can apparently not be used directly to simulate roughness - see the figure below.



Many configurations of surface degradations were measured in the wind tunnel. Examples are: Sandpaper at the leading edge (in reality caused by erosion), cavities in the surface (in reality caused by de-lamination) and zigzag tape at the leading edge (in reality bugs at the leading edge). With these measurements it is now possible to estimate the decrease in lift and the increase in drag caused by the surface imperfections at blade sections that should be measured by the photogrammetry based on the drone flights. With such data the loss in aerodynamic performance from the rotor can be predicted.

During the lifetime of the project we were invited to conferences directed towards the industry to present our work in LER[30,31]. Participations in these workshops gave us valuable connections and feedback.

Achieved objectives – Why/Why Not:

The majority of objectives were fulfilled for this milestone, where a lot of knowledge has been gained and technology been build up. The original idea was to go with a drone to several wind turbine blades and also get access to several unmounted wind turbine blades that was placed at the ground to investigate the different types of damages. Furthermore, it was expected to carry out wind tunnel tests at an earlier stage in the project to investigate the aerodynamic performance of the damages. However, these original ideas were more challenging than expected. The damage types on wind turbine blades were not investigated as expected, but through photos in inspection reports. Thus, the damages were not quantified to the same level as expected, however, the damages were varying a lot and therefore it was more important to categorize the types than getting knowledge of the exact geometry of the damages.

Dissemination:

Article [28] was made in connection to the Torque 2016 conference in Munich, where many researchers and development engineers from the industry were attending. This conference is the most important conference within research and development in wind energy. Going to this conference was important to underline that we in this project are in the forefront and that we are gaining knowledge in the effect of leading edge roughness.

Article [29] was made in connection to the Torque 2018 conference in Milan. This conference is organized every second year and is in line with the above conference. Going to this conference was important to underline that we in this project are in the forefront and that we are gaining knowledge in both the effect of leading edge roughness, but also how the leading edge roughness can be compensated.

Presentation [30] was carried out at the WESC2019 conference. Attending this was important to let the research and development engineers know that we have obtained a significant knowledge base and that DTU and Power Curve have important knowledge in this area.

Presentations [31] and [32] were made at conferences with attention from mainly the industry. Due to the organizers knowledge of our competences within leading edge roughness we were invited to give a presentation. The objective of this conference was two-fold: 1) We got knowledge of which problems that the industry had and 2) we got the possibility to tell about our ideas and make it clear that we had significant knowledge with LER that almost nobody has.

References:

[27] Olsen A S, García N R, Bak C, Gaunaa M, Improved Roughness Model for 2D Viscous-Inviscid Panel Methods, WESC 2017 Conference, Technical University of Denmark, 28 June 2017

[28] Bak C, Gaunaa M, Olsen AS, Kruse EK. What is the critical height of leading edge roughness for aerodynamics? Journal of Physics: Conference Series (Online). 2016;753. 022023. https://doi.org/10.1088/1742-6596/753/2/022023

[29] Bak C, Skrzypiński W, Fischer A, Gaunaa M, Brønnum NF, Kruse EK. Wind tunnel tests of an airfoil with 18% relative thickness equipped with vortex generators. Journal of Physics: Conference Series. 2018;1037(2). 022044. https://doi.org/10.1088/1742-6596/1037/2/022044

[30] Bak C, Olsen A S, Gaunaa M, Mikkelsen R, Fischer A, Beckerlee J, Ildvedsen S, Kruse E K, Brønnum N F, Investigation of leading edge roughness on an airfoil in the Poul la Cour Tunnel, WESC 2019, Cork, 19 June 2019

[31] Bak C (invited speaker), Quantifying leading edge roughness (LER), its impact on AEP and how to reduce this influence on blade performance Blade Inspection Damage and Repair Forum, Amsterdam Marriott Hotel, 10 Oct 2016

[32] Bak C (invited speaker), Olsen A S, Sørensen N N, Kruse E K, Brønnum N F, Madsen C B, Nikolov I A, Garnæs J, Nielsen M S, Understanding the Causes of Blade Surface Damages and Their Influence on Energy Output, Blade O&M Europe, 12-14 March 2019, Amsterdam

5.4.3 Annual Energy Production Estimates (Power Curve)

M3.4 Influence of leading edge roughness on Annual Energy Production

Objectives:

- Create a “damage” matrix
- Match scanned damage with best fit in damage matrix
- Calculate total AEP loss due to blade damages

To be able to utilize the results from the project commercially it was necessary to have a reliable, precise, robust and automatic method of calculating the AEP loss. To achieve this the above-mentioned objectives must be completed.

The expected outcome of the objectives includes an intuitive script/algorithm that can produce a large matrix of damages with various depth, length and angle combinations in a reasonable amount of time. Furthermore an optimization algorithm to find the best fit between the damage obtained from the SfM and damage matrix. Lastly a BEM code should be created to calculate the AEP loss based on the damage found as best match.

Main activities:

Based on experience and visual inspection of some decommissioned damaged blades some important parameters to describe a damage was established. MATLAB was utilized to write a script which could produce a matrix of damages varying the different parameters describing a damage in a resolution chosen by the user, this was done to obtain a “database” of damages which covered the types of damages encountered. Also a naming convention was created to identify each unique damage.

Next step was creating an optimization algorithm to find the best match between a 2D slice of the scanned damage and the damages in the database. The XY-coordinates of the scanned slices are placed arbitrary in space meaning that the profile can be both rotated, translated and scaled differently compared to the standard notation used for the profiles in the damage database. The profiles in the databased are defined with the LE starting in (0,0) and TE in (1,0). So first the scanned profiles are rotated, translated and scaled to fit this definition then an optimization algorithm is utilized to find the best match by finding the case with the minimum Euclidian distance between the two profiles.

Each damage in the database have been modelled in CFD to calculate the effect of the damage on lift and drag, these polars for each damage are utilized as input for a BEM code to calculate the AEP loss of the turbine. The BEM code is created to calculate the power production of different blade sections along the blade and summing them using knowledge of the blade planform and profile polars. This is done both for the clean profiles and the damaged profiles found from the optimization algorithm based on the scanned 2D slices and the percentwise difference is then calculated.

Results:

See milestone 4.1 for results of this task.

Achieved objectives – Why/Why Not:

The objective was achieved with room for further development and improvement. However, the method is proven concept.

Dissemination:

A PhD thesis has been finalized based on the research and findings during the project and valuable state of the art knowledge about LER and its effect on reduction in turbine AEP has been integrated into Power Curve. Several research articles have been written about the project and have been published in relevant journals, based on the articles a number of conferences were attended to disseminate the findings from the project. The conferences made it possible to share insight and non commercial related progress on the project subject with the wind power community to further advancement for the technology.

5.5 WP4 - Full scale validation of LEP wind turbine technology platform

M4.1 – Field trials conducted and documented

A full scale test validation of the system in "real life" conditions was planned to begin halfway through the project in cooperation with E.on and or Vattenfall. At this point in the project some problems regarding WP1 and the UAV system had already been encountered, this meant that the system was not ready for a full scale test and adding to this it also looked difficult to gain access to a wind turbine on land with a significant amount of LER and within a reasonable radius to actually test the system. The solution to this became constructing a test rig in the backyard of Power Curve consisting of a gantry with the outer tip of a real blade hanging down. Based on own experience and visual inspections of decommissioned blades similar LER damages was made on the LE of the blade in the test rig, images of this can be seen below.

a) b)

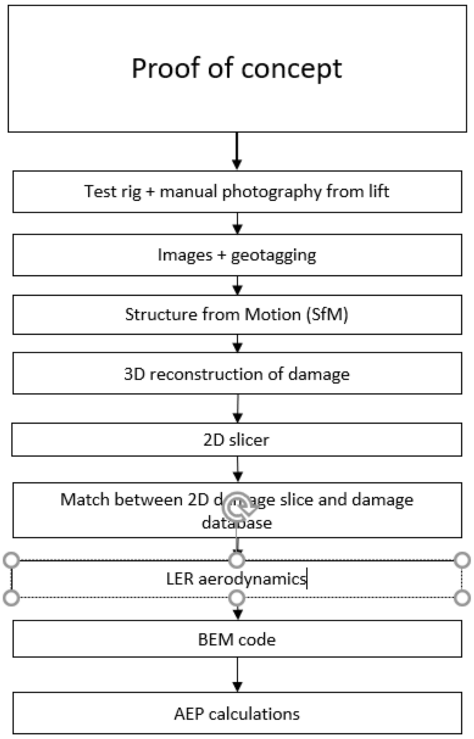
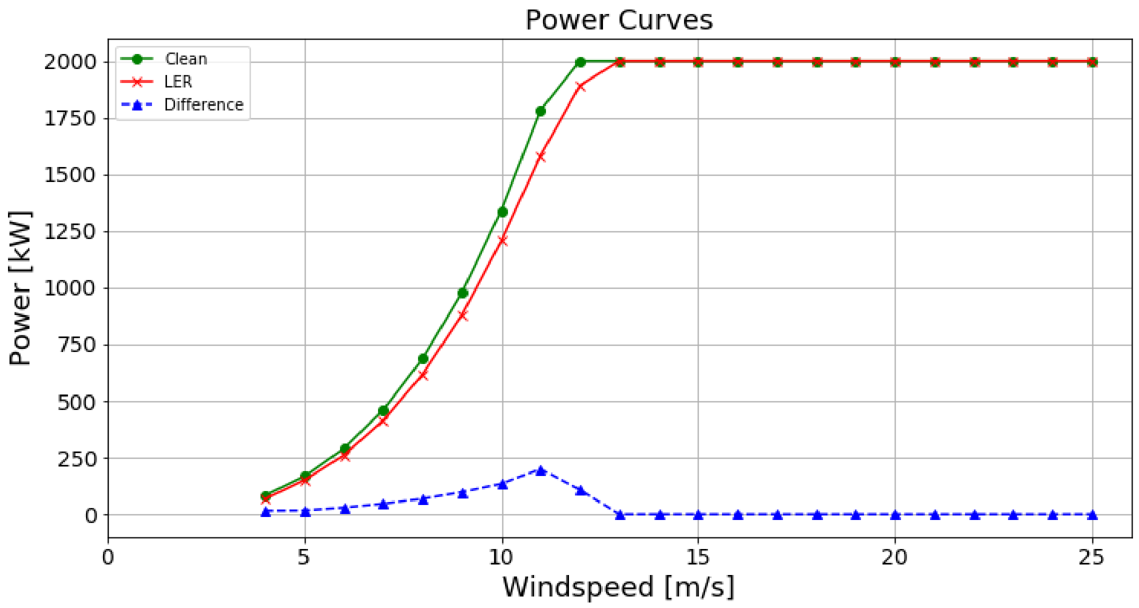
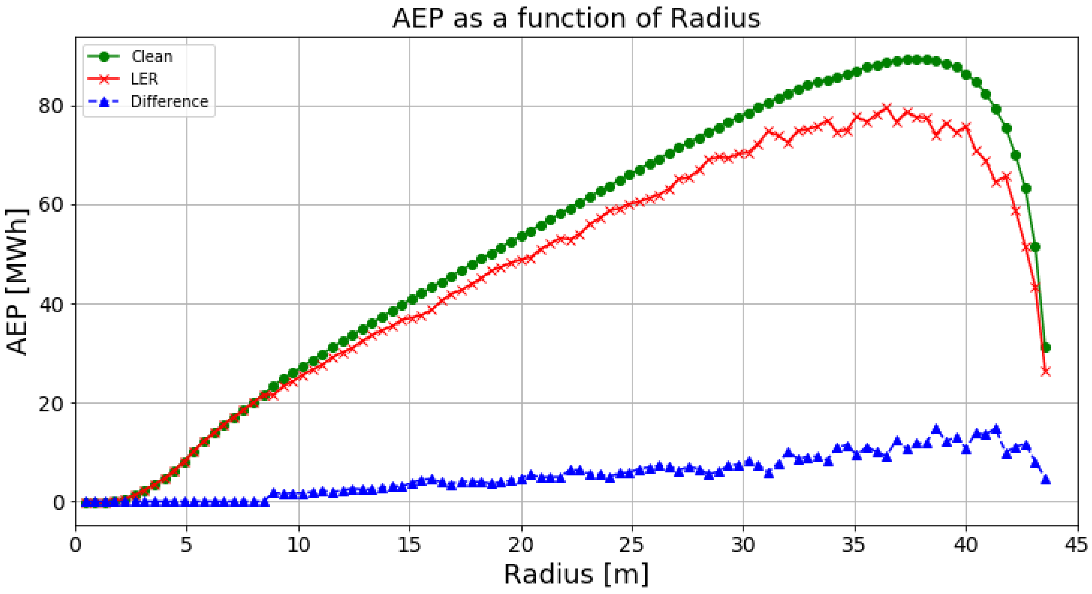


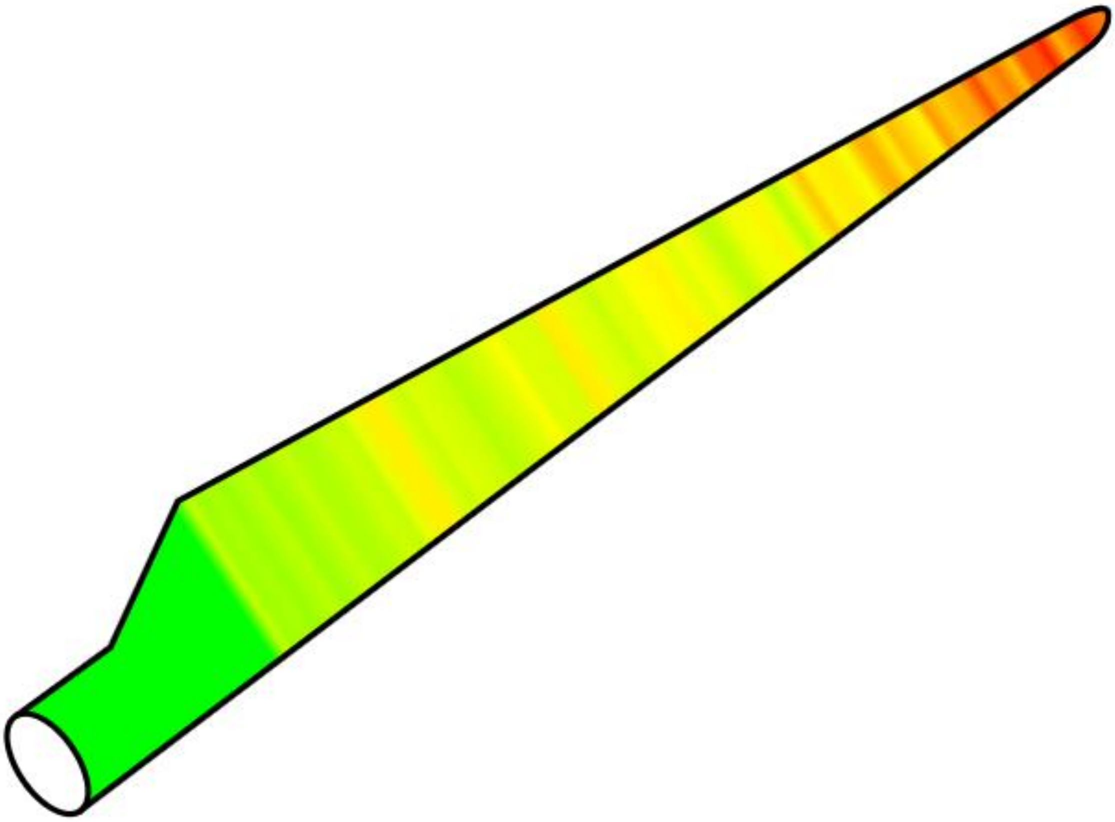
Figure a) showing the test rig and figure b) showing the LER of the blade. The test rig meant easy access for testing of the system when the weather allowed it, this would not have been the case on a real turbine which have a lot of logistical problems associated with testing. During a field trial of the UAV autopilot system the drone crashed meaning that no further development of the autopilot could be tested until spare parts were received, this delay meant that a full scale test of the system would not be possible within the timeframe of the project. The goal from that point was therefore to make a proof of concept of the project in a more manual way. The steps of the procedure can be seen in the block diagram.

Results:

The results shown are based on the proof of concept procedure where one damaged patch have been photographed manually from a lift in a semi-circle around the blade hanging in the test rig to get images from multiple angles. The images of the damaged patch have been utilized in the SfM software to obtain a 3D model of the damage, the 3D model have been sliced into 2D slices each 2D slice have been matched against a damage from the damage database made in CFD this damage have then been extended on most of the blade. Data from the clean blade and the damaged blade are used in the BEM code to obtain the AEP loss for each radial position of the damaged blade. The results are shown below, where the first graph shows the power curve for both the clean case (green) and the LER case (red) together with the difference between them. The second graph shows the AEP as a function of the radial position on the blade, where it is possible to see that the same damage have a higher impact on the AEP on the outer part of the blade. The last figure visualizes this with a green colour indicating no impact on AEP, yellow indicating medium impact on the AEP and red indicating severe impact on the AEP. The calculations for the proof of concept showed an AEP loss of 7.16% due to LER.


Power Curves
Clean
LER
Difference
2000
1750
1500
1250
1000
750
500
250
0
Power [kW]
0
5
10
15
20
25
Windspeed [m/s]


AEP as a function of Radius
Clean
LER
Difference
80
60
40
20
0
AEP [MWh]
0
5
10
15
20
25
30
35
40
45
Radius [m]

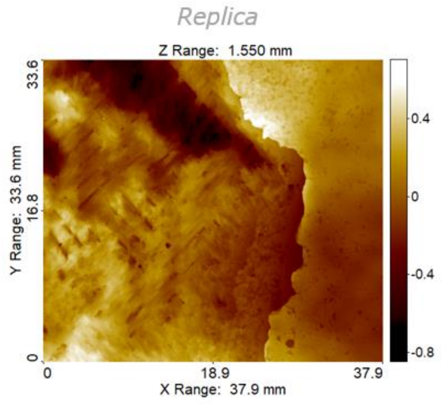
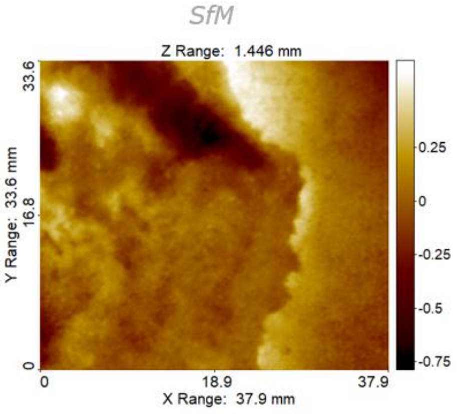
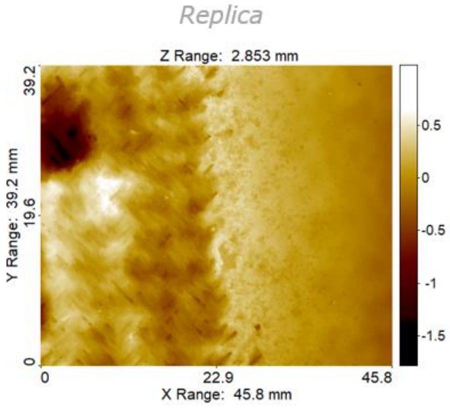
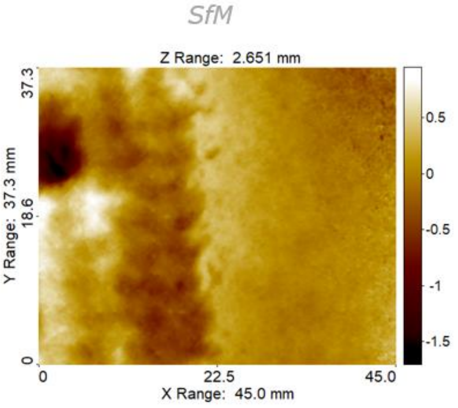
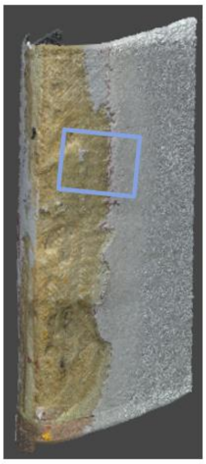
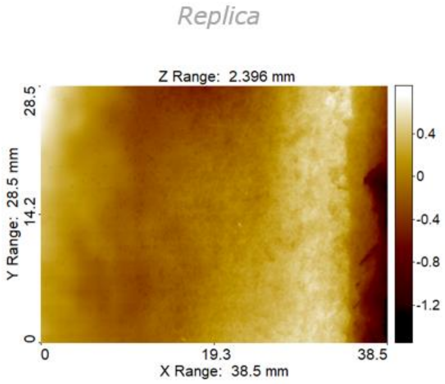
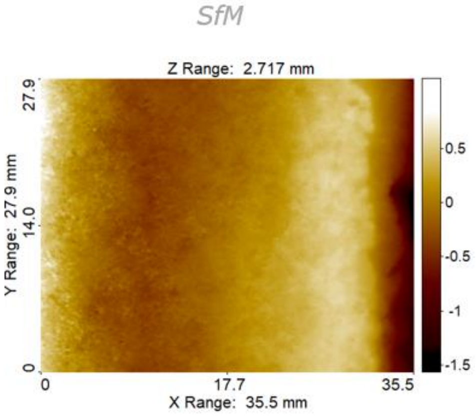
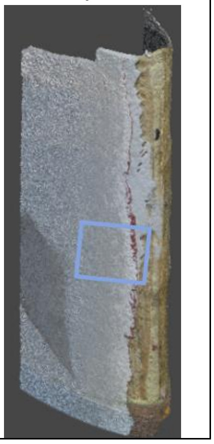


M4.2 Transportable microscope used in the field

It was clear early in the project that a transportable microscope was unpractical compared to alternative methods (see WP2 for elaboration). It was decided to do a field test by replicating damages in 5 different places on a real blade, measure them in the laboratory and compare them to a 3D reconstruction made on the same real life blade.

DFM visited Power Curve to make the replica on the test rig (see 4.1). Below figure shows DFM doing the replica on the real blade.

The below figures show on the Left, Replica made in laboratory (see WP2) (High Fidelity), in the middle, the same patch made from SfM (see WP1), and on the right, the location of the patch on the blade tip, shown on the 3D reconstructed blade section. Only 3 out of 5 replicas a shown as the results are similar.

1/5 	1/5 	1/5 
2/5 	2/5 	2/5 
3/5 	3/5 	3/5 

The correspondence between replica and SfM good. The larger steps are caught whereas the very small roughness is uncaught. With the purpose of aerodynamic calculation in mind, the result is satisfying. NOTE THAT the 3D reconstruction is used in the proof of concept in the previous milestone M4.1.

5.6 WP5 - Implementing the knowledge into Power Curve

The major tasks and milestone for this WP was:

M5.1: A technology transfer plan for efficient and due transfer

The PhD student has been working deeply into especially WP3. A lot of time has been spent in WP1 and some time has been spent on WP2. By doing this, Power Curve has secured a technology transfer after the project period ends. All results and files has been shared with the PhD student and are saved in Power Curve. The PhD student has spent a lot of time understanding all important aspects of each WP and sub tasks, by frequent stays or visits at AAU, DTU and DFM.

M5.1: A submitted PhD thesis

A PhD thesis is in writing where 4 articles will form the scientific basis. A lot of work not suitable for articles due to either being too application specific or due to Power Curve ApS IP rights will be presented in the thesis, preferable under non-disclosure. The deadline is 30th August 2019.

6. 1.6 Utilization of project results

The expected TRL after project end was 7-8 this was based on no delays or unexpected problems. A greater work load than expected and problems encountered especially with regards to the UAV means that the achieved TRL is more in the range 3-4. Meaning that all steps of the process can be done and demonstrated but in a more manual way than expected due to mentioned problems with the UAV autopilot.

A commercially ready product at TRL 7-8 was not achieved since some of the process are still semi manual at project end. Further development is needed to take the project to the next step and make it commercially ready. A new project proposal with the same project partners and including new ones have therefore been created called AeroMax which aims to mature the technology and take it to TRL 8. A TRL of 8 and a commercially ready product would mean possibly new employments in Power Curve and products added to the portfolio.

Despite the technology not being commercially ready a large amount of knowledge and technical understanding have been added to Power Curve in form of the industrial PhD, furthermore contacts and meetings with external partners have been formed during the project. Lastly as a direct spin-off and a connection established based of the project Power Curve has hired a new employee with experience in LER and wind turbines.

7. 1.7 Project conclusion and perspective

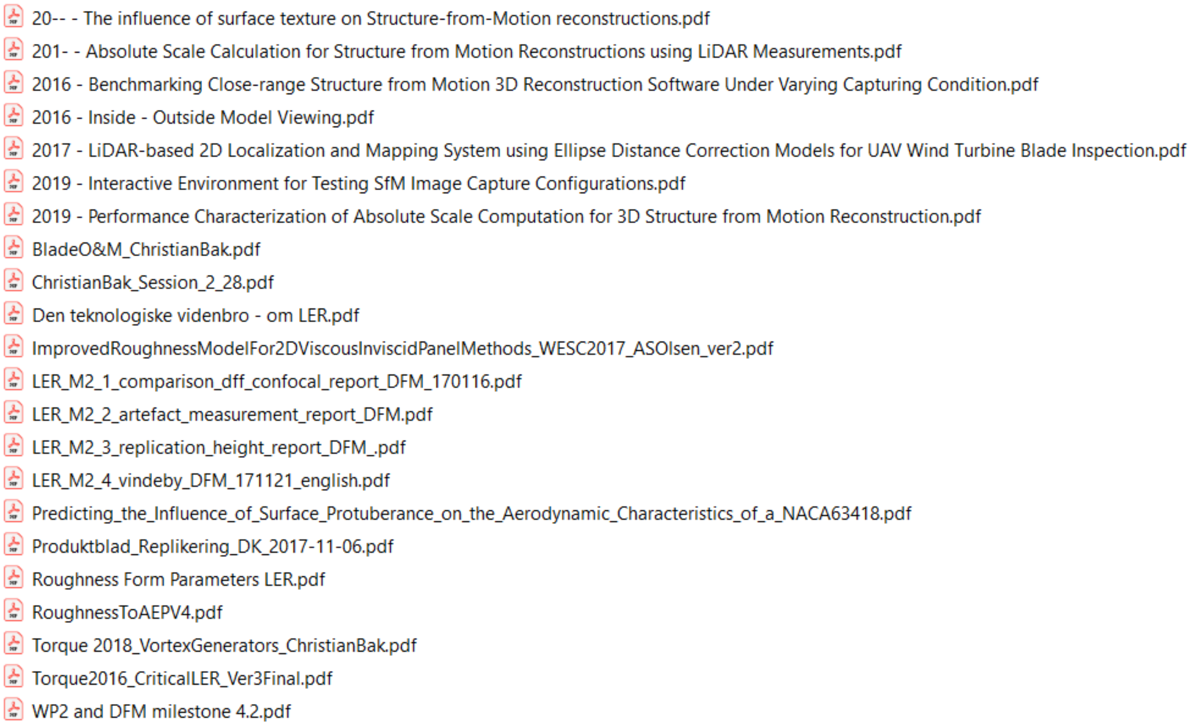
Each section in this report contains small part conclusion. The governing conclusion is that the project is still highly relevant in both academia and the industry. The road from development to demonstration and commercialization still lies ahead. Multiple technologies used in the project were at a lower TRL than expected at project start. These technologies have been taken from TRL 0/1 to 3/4 during the project, where it was expected to start at 3/4 and take it to 7/8. The result is that most of the technologies are ready for further maturing and demonstration, hence a new project application has been submitted, named “AeroMax”. The system developed in the project has been tested in a proof of concept in WP4. The results are promising but further development is needed especially on the drone autopilot part.

The interest from wind turbine owners is still high and the demand for wind turbine power analysis is higher than ever with the still increasing number of wind turbines world wide.

8. Annex

The below listed files can be downloaded from:

https://powercurve.sharepoint.com/:u:/s/PowerCurveApS/EU7jTXKrg0ZGt0JksAZkkIIBnwxxGAu6QnJsF4ELVbr5Ew?e=YgeqMy



20-- - The influence of surface texture on Structure-from-Motion reconstructions.pdf
201- - Absolute Scale Calculation for Structure from Motion Reconstructions using LiDAR Measurements.pdf
2016 - Benchmarking Close-range Structure from Motion 3D Reconstruction Software Under Varying Capturing Condition.pdf
2016 - Inside - Outside Model Viewing.pdf
2017 - LiDAR-based 2D Localization and Mapping System using Ellipse Distance Correction Models for UAV Wind Turbine Blade Inspection.pdf
2019 - Interactive Environment for Testing SfM Image Capture Configurations.pdf
2019 - Performance Characterization of Absolute Scale Computation for 3D Structure from Motion Reconstruction.pdf
BladeO&M_ChristianBak.pdf
ChristianBak_Session_2_28.pdf
Den teknologiske videnbro - om LER.pdf
ImprovedRoughnessModelFor2DViscousInviscidPanelMethods_WESC2017_ASOlsen_ver2.pdf
LER_M2_1_comparison_dff_confocal_report_DFM_170116.pdf
LER_M2_2_artefact_measurement_report_DFM.pdf
LER_M2_3_replication_height_report_DFM_.pdf
LER_M2_4_vindeby_DFM_171121_english.pdf
Predicting_the_Influence_of_Surface_Protuberance_on_the_Aerodynamic_Characteristics_of_a_NACA63418.pdf
Produktblad_Replikering_DK_2017-11-06.pdf
Roughness Form Parameters LER.pdf
RoughnessToAEPV4.pdf
Torque 2018_VortexGenerators_ChristianBak.pdf
Torque2016_CriticalLER_Ver3Final.pdf
WP2 and DFM milestone 4.2.pdf