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Autonomous surface inspection of wind turbine blades for quality assurance in production

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Abstract

This paper defines a method, and associated automated system, for production inline inspection of the surface geometry of wind turbine blades which can be plugged directly into existing production facilities without changing the setup. During current production, turbine blades are manually inspected, and this system aims at automating this process. Various geometrical defects can occur in the surface during production and these defects can lead to shortened life times and lowered power output of the turbine. Automating the inspection process requires a method which is at least as sensitive as the currently used manual process while significantly lowering the time consumption. It is shown that the proposed method is fast and has the potential to deliver the high precision and resolution needed to resolve both small and large scale surface defects.

1. Introduction

Wind turbine blades are usually made by infusion moulding where multiple layers of fiberglass or carbon fibre are infused with epoxy resin to create a strong, flexible mesh. This method has numerous advantages (1), but is vulnerable to several failure modes, such as wear on the moulds, erroneous packing of the fiberglass, sliding of the fiberglass, post-moulding treatments such as sanding, plastering and painting etc. Each of these failure modes can impact a blade’s final surface geometry, transforming it away from the intended, optimized design with reduced lifetime and power generation as a result. Surface quality inspection is used to ensure that blade specifications are complied with and to identify the causes for defects and to eliminate these causes.

Generally, defects occur on two spatial scales. The first are submillimetre which originates from the various surface treatments that the blade undergoes. Examples are pinholes, cracks, steps etc., all of which can hinder laminar air flow and create damaging surface erosion. The second scale is decametric with defects being introduced during the moulding process and seen as deviations in the surface trajectory relative to its design, causing suboptimal lift. Both types of defects are most devastating if positioned on the blades leading edge, why this part of the surface is in focus. In current production, these defects are detected through manual inspection.

This paper investigates a method for in-line, autonomous surface quality inspection of wind turbine blades. The method has the potential to significantly reduce inspection cost and time, while even further enhancing the already good accuracy and precision of currently used, manually based surface inspection processes. In addition, it can create a highly detailed virtual copy of the blade surface, which can be used in an Industry 4.0
setting (2) for simulations, documentation, planning, etc. The two main contributions of this paper are as follows:

1. Development of method to automate wind turbine blade surface digitalization and inspection.
2. Investigation of the measurement uncertainty of this method.

The inspection method materializes as a robotic system composed of a measurement system which is moved over the blade surface by a locomotion system to survey the entire leading edge. This system is illustrated in Figure 1.

![Figure 1. Sketch of the inspection system.](image)

According to the ISO 2859 series, quality inspection is composed of two steps, namely: 1) conducting measurements and 2) decide upon conformity with specification. This paper focuses on the measuring step, although a novel idea for comparing measurements and 3D CAD model is also presented.

Schubel (3) showed that fully automating the wind turbine blade production line can significantly reduce manufacturing costs. The automated inspection method proposed here is designed to be operational within current production environments without any alterations, allowing for gradual automation. Albeit easing integration and flexibility, this restriction introduces several design challenges. An industrial wind turbine blade is a slender object with lengths currently up to 88.4 meters. When moving through the production line, a blade is placed in a two-wheeled carriage. There is no fixed transformation between the carriage and the blade coordinate frames, or between the carriage and the production floor, why an automated system has to plan its inspection path online in order to adapt to the position of the surface.
2. Previous work

Large scale geometrical metrology has been an active area of research for many years (4) with significant developments in measurement methods and applications (5,6). This section outlines the contributions which influenced the choices taken when designing the inspection method.

A general overview of current large scale metrology measurement methods was presented by (7). It was concluded that conventional tactile CMMs are generally only applicable for objects with ranges lower than 10 [m] and that target based photogrammetry is faster than tracking based laser systems and retains comparable measurement accuracy when demonstrated on a 25 [m] long train wagon.

A coherent laser radar system was used to measure the geometry of a composite ship hull by (8). It was found that coherent laser radar outperformed laser tracking and time-of-flight scanning. The 215 [m²] surface of the ship hull was scanned with a resolution of 10 [mm] and an accuracy of 0.5 [mm] in 30.5 hours. The process required that the laser radar was moved several times, why spheres were mounted on the hull for aligning the measurements.

Several relevant contributions have been made in the wind power domain. In (9) a Microsoft Kinect mounted on an industrial robot was used to inspect a down-scaled version of a turbine hub. It was demonstrated that the CAD model can be used to plan the robot motion based on a set of Critical-To-Quality parameters and that these parameters could be measured from the 3D scan data.

A system composed of several laser trackers was used in (11) to sample blade profile curves which were then aligned to the CAD model to do in-field inspection of installed wind turbine blades.

To the extent of our knowledge, the first idea for a practical, autonomous, inline quality inspection system for surface geometry on industrial sized wind turbine blades was presented by (12). The system is composed of a linear drive stage and two 2D laser line scanners, one mounted on either side. The linear drive is placed beneath the blade which is suspended from the root end. The system was, however, only demonstrated on a small blade with a length of 2 meters, and it is thus unknown how the system would perform on a large blade.

An inspection system composed of a linear drive stage, an industrial 6 Degree-of-Freedom (DoF) robot arm, a structured light 3D scanner and a laser tracker was proposed by (13). In addition to discuss the various difficulties of registering measurements with the CAD model, the paper successfully demonstrates that such a system can provide accurate and dense measurements of blades with a length of up to 12 [m]. Blades were mounted in a special fixture and the scan path pre-programmed offline.

Coherent laser radar was used to inspect blade surface geometry in (14) and (15). The papers describe the measurement strategy, but focus on the measurement analysis and registration. Like (8), their method requires that the laser system is moved several times to cover a 60 [m] blade. The method is not demonstrated on a full blade.
3. Method for autonomous blade surface inspection

The measurement system presented here is composed of a high-resolution, structured light based 3D scanner and a local positioning system. The locomotion system is composed of a six-axis industrial robot mounted and a moveable platform, and this design is described in the following.

3.1 Requirements

Manufactures impose several soft requirements for blade surface inspection. They are denoted soft requirements as they are closer to guidelines than actual hard, numerical requirements. These are established through interviews with manufactures, form the basis for the system design, and are highlighted in Table 1.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>The sensitivity must be high enough to detect discrete defects with a spatial distribution covering only a few hundred micrometres.</td>
</tr>
<tr>
<td>Range</td>
<td>The measurement range must be large enough to cover defects with a spatial extend from a few hundred micrometres up to a few meters.</td>
</tr>
<tr>
<td>Speed</td>
<td>The number of consumed operator hours per blade must be lower when compared against current methods.</td>
</tr>
<tr>
<td>Deployment</td>
<td>The method must be easily deployable in the current production environment and flexible enough to be conducted at various sites around the factory.</td>
</tr>
<tr>
<td>Cost</td>
<td>Procurement and running costs must be low enough to yield a positive business model.</td>
</tr>
<tr>
<td>Safety</td>
<td>The health of operators and co-workers must not be put at risk by the method.</td>
</tr>
</tbody>
</table>

3.2 The measurement system

Several technologies for measuring the blade surface are available. Inspired by (13), a Structured Light (SL) based 3D scanner was selected, which projects a 2D pattern onto the surface which is then distorted by the surface’s curvature. This distortion is sampled by one or more camera(s). The 3D structure of the surface can be reconstructed digitally as a point cloud from the image(s). This method excels by its high resolution, relative low uncertainty and high data rates, but is limited by the optical properties of the surface and the field of view and focus distance of the cameras. Many other 3D scanning technologies exist, each with its own pros and cons, but it was found that they require significantly longer time to achieve the same resolution as SL scanners (16). The scanner must have the following properties:

- A resolution and precision which is high enough to resolve the small scale defects.
- An optical system which makes it operational in the light conditions present at the production floor.
- A reconstruction time that is significantly short, preferably less than five seconds.
The RapidScan from Automated Precision Inc. (API) was chosen as it delivers a good compromise between cost and performance. It uses invisible near infrared light which is not emitted by energy saving overhead lights, why they will not interfere with the projected pattern. A pilot study proved that the paint used for turbine blades does not pose problems as it has a nice high albedo and low scattering. Note that this would not have been the case if the blade were to be scanned before painting, as the composite material observes strong scattering properties. From its specifications, the RapidScan has a measurement area of 300 by 300 [mm] at a distance of 350 [mm], with a point spacing of 200 [µm] and a point uncertainty of 50 [µm].

3.2.1 Scanner tracking
As indicated above, the SL scanner covers only a small fraction of the entire blade surface per scan, why it must be moved across the surface. See Figure 2 for an illustration. As the scanner moves, its position has to be tracked in a global coordinate frame such that consecutive scans can be transformed into that same reference frame. This is necessary as it is difficult to accurately register neighbouring scans to each other using post-processing alignment strategies, such as ICP (17), because the blade surface is very monotonous.

Again, several different technologies are available for tracking, but a laser tracker with an active target was selected. This combination can provide 6 DoF positions with an uncertainty below half the minimum point-to-point distance of the scans. The laser tracker and active target delivers high data rates, with positions many times per second. From trials, it is known that this combination is significantly faster than measuring four passive targets and then assign a coordinate frame to the measurements, as done in (13).

It was found that a combination of API’s vProbe active target and their OmniTrack II laser tracker provided a good compromise between price and performance. The vProbe is closely aligned with the internal coordinate frame of the scanner in order to adhere to the Abbe principle. The combined measurement system is sketched in Figure 3.

![Figure 2. Illustration of the area covered by the scanner (green) based on the frustums of the two cameras (grey). The angle between the scanner view w (blue) and the surface normal n (red) should be small to increase precision, but α > 0 to avoid specular highlights.](image)

![Figure 3. Sketch of the measurement system.](image)
3.3 The locomotion system

A six axis industrial robot arm was chosen for carrying the scanner. The versatility of the robot makes it a good platform for moving the scanner around the leading edge and track the course of the surface. By mounting the robot on a moveable platform, the working envelope of the system is greatly increased, allowing it to survey the entire leading edge.

Health and safety are major concerns for manufacturers. Because of that, a collaborative robot (cobot) was selected. Of the various available options, the Universal Robots UR10 fits nicely with the specifications. It is relatively cheap, adheres to ISO standard 15066 about collaborative robots, has an Ethernet interface for computer communication and control, digital interfaces for low level PLC communication, and it has a fairly large working envelope.

3.4 System calibration

The system contains six local coordinate frames, with a chain of five rigid transformations combining them. Starting from the bottom, $T_{fr}$ transforms coordinates from the moving platform, or frame, to the robot base. $T_{rt}$ transforms from the robot base to the robot tool centre point (TCP). $T_{rs}$ transforms from the TCP to the scanner. $T_{sp}$ transforms from the scanner to the tracking probe. $T_{pg}$ transforms from the tracking probe to the global coordinate frame defined by laser tracker. The transformations are illustrated in Figure 4. All of the transformations have to be known in order to control the robot and transform the measurements into the same reference frame.

$T_{rt}$ is given as the robots position in its own coordinate frame and $T_{pg}$ is given as the measured six DoF position of the tracking probe using the laser tracker. The remainder transformations, $T_{fr}$, $T_{rs}$ and $T_{sp}$, must be obtained through calibration.

$T_{fr}$ is estimated from the CAD design model of the inspection system. $T_{rs}$ is computed using the hand-eye calibration from (18). To calibrate $T_{sp}$, a set of four Spherical Mounted Reflectors (SMR) are mounted in sockets on the scanner whose positions in
the scanner coordinate frame is calibrated by the manufacturer. From measurements of the positions of the four SMRs and the probe, $T_{sp}$ can be computed using least squares optimization.

### 3.5 Control of the surveying process

The scanner tracks out a U-shaped trajectory over the blade surface, going forth and back to cover the leading edge. This trajectory is illustrated on Figure 5. The robot makes six stops on every U-curve to sample the surface. The API scanner captures the necessary data in two seconds and the 3D point cloud is reconstructed while the robot moves to the next sample position. The robot can reach two U-curves from one position and then the platform has to be moved. The two U-curves will yield a total of 12 point clouds which are used to plan the next sample positions on the following two U-curves, and the movement of the platform. The 12 point clouds are projected into the coordinate frame defined by the moveable platform, combined, and sliced by a transverse plane through the middle. Points located up to 5 [cm] away on both side of the plane are projected onto the plane, and a 2D polynomial path is fitted to these points. The method presented here is based on (19), but replaces spline curves with polynomials to enforce a stronger prior on the surface trajectory. Six points are sampled from the polynomial path based on their arc-length from the leading edge. There should be more sampled points in areas where the surface curvature is big compared to areas where the curvature is small. The six points are then back-projected into the 3D coordinate frame and copied for a total of 12 points. The first point set copy is slid backwards to cover the first U-curve and the second is slid forwards to cover the second U-curve. The process is illustrated on Figure 6.

**Figure 6. Illustration of the sample point planning.** The sampled 3D point clouds from the previous sample positions are sliced by a transverse plane and a polynomial path is fitted to the points projected onto this 2D space (a). The green line shows the model and the blue points and arrows indicate the computed sample positions. The positions are projected back into the 3D space, copied, and moved both backwards and forward along the longitudinal direction (b).
4. Measuring performance of the method

In order to assess the measurement performance, the guidelines in VDI/VDE 2634 was used, which is based on a calibration artefact, and not the measurement of the turbine blade. It specifies probing error, sphere-spacing error and flatness which, in combination, hint about the measurement uncertainty of the 3D scanner. Traceability is established through the use of a 200 [mm] long ball-bar standard with 25 [mm] diameter spheres and a 200 [mm] by 50 [mm] flatness standard, both which were calibrated and certified by Ingenieria Y Servicios De Metrologia Tridimensional Sl (ISM3D). The ball-bar was used to estimate both the probing and sphere-spacing error. More details on the standards and the general procedure can be found in (20). The inspection system was positioned roughly 5 meters from the laser tracker. The ball bar and flatness plane was measured in the required positions relative to the scanners frustum by moving the scanner with the robot. The measurements, transformed into the global reference frame, are shown on Figure 7.

![Figure 7. 3D point clouds from measurements of ball bar (a) and reference standards (b). Each individual measurement has been assigned a distinct color.](image)

During analysis, it was noticed that the scanner struggled to accurately reconstruct the spheres near the rim where the angle between the view direction and surface normal approached 90º. An example is shown in Figure 8.a. As the guideline operates with maximum values, these points dominate the error measures. Thus, it was deemed necessary to remove them. The distribution of centre-to-point distances, over all measured spheres, is depicted in Figure 8.c. By fitting a Gaussian distribution and setting a threshold at four standard deviations, it was possible to remove the points. Ten randomly selected spheres were visually inspected in order to verify that the correct points were removed. In addition, the 0.3% points which contributed the largest error was removed as is allowed by the guideline. The results are presented in Table 2. The variables in the table are as follows: $P_F$ is the form probing error, $P_S$ is size probing error, SD is sphere-spacing error and F is flatness measurement error. Results from the unfiltered measurements are denoted “Original” and results from the filtered measurements are denoted “Filtered”.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Original</th>
<th>Filtered</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_F$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_S$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td></td>
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</tbody>
</table>
Figure 8. Examples of point clouds from reference standard measurements. Red points are extremum points which are omitted as per VDI/VDE 2634. (a) shows one sphere from the ball bar with fictional points protruding from the rim. (b) shows the same sphere but with the erroneous points detected and highlighted in orange. The colouring of both point clouds illustrates the normalized distance from the sphere’s centre to the points. (c) shows the distribution of point-to-center distances among all spheres. (d) shows the flatness plane with points coloured by their distance over the fitted plane. This is also a point cloud, but sampled so densely that it looks solid.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Std.</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_F) original</td>
<td>1.248</td>
<td>0.301</td>
<td>0.694</td>
<td>2.069</td>
</tr>
<tr>
<td>(P_F) filtered</td>
<td>0.585</td>
<td>0.115</td>
<td>0.391</td>
<td>0.983</td>
</tr>
<tr>
<td>(P_S) original</td>
<td>0.814</td>
<td>0.444</td>
<td>0.221</td>
<td>1.827</td>
</tr>
<tr>
<td>(P_S) filtered</td>
<td>0.373</td>
<td>0.309</td>
<td>-0.309</td>
<td>1.401</td>
</tr>
<tr>
<td>SD original</td>
<td>0.399</td>
<td>0.162</td>
<td>-0.032</td>
<td>0.855</td>
</tr>
<tr>
<td>SD filtered</td>
<td>0.245</td>
<td>0.142</td>
<td>-0.204</td>
<td>0.680</td>
</tr>
<tr>
<td>(F)</td>
<td>0.173</td>
<td>0.029</td>
<td>0.115</td>
<td>0.233</td>
</tr>
</tbody>
</table>

Filtering of the ball bar point cloud significantly improved the associated error measures, but as the guideline specifically concerns maximum values, the measurement uncertainty of the system should be the 1.4 [mm] obtained from the proofing error, \(P_S\). However, based on the low mean values and low standard deviations, it is believed that some noise points still linger in the measurements of the ball bar. It is assessed that the actual measurement uncertainty is lower than 0.7 [mm], but a more thorough investigation is needed to definitively establish the uncertainty.

An example of a measured blade section is showed on Figure 9. The example section is four meters long and composed of 70 individual point clouds for a total of roughly 45 million individual points. The inspection system has successfully been tested on blade
sections of up to 19 meters in length, which was scanned in 1 hour and 15 minutes, with the scanners shutter time being the bottleneck.

![Figure 9. Example of a measured blade section. Note that this is not the surface has not been reconstructed, but that it is sampled so densely that it looks like a surface. This section is approximately three meters long.](image)

5. **Idea for automatic detection of surface defects**

As detailed by the previous work, in particular (13), the flexibility of the material combined with the size of the blades pose a significant challenge when registering the point clouds to the blade CAD model. Previous work indicates that registration through finite element modelling is difficult due to production tolerances and the properties of the composite material. Instead, it seems that it would be easier to achieve the required accuracy through a local method.

It is proposed to take the local fitting to limit. A plane would be aligned to the second and third principal components of the point cloud and slided down the first principal component. For each slide, a small volume of nearest points around the plane would be cut out and registered separately to the blade CAD model, but regulated in a bundle adjustment setting (21) which allows only a certain, small deviation between overlapping scans. In this way, the low frequency changes attributed to gravitationally induced deformations would be handled through the registration, while still retaining the possibility to detect higher frequency surface changes stemming from defects.

6. **Conclusions**

This paper developed an autonomous inspection system for wind turbine blade surfaces. It was found that a combination of a structured light 3D scanner and a laser tracker with an active target formed a good measurement system, and that the range of this system could be extended by an industrial robot mounted on a moveable platform. It was shown that the system is fast and achieves low measurement uncertainty on the investigated calibration artefact, though more thorough uncertainty investigations are needed. The results documented here and the experiences with the system show a great potential of the system in practical blade manufacturing. Future work will focus on fully automating the blade inspection by further investigating the measurement uncertainty and developing automatic registration and comparison between measurements and model. Hereby, the current manual process can be completely replaced.
Acknowledgements

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References and footnotes