Development and metrological validation of a new automated scanner system for freeform measurements on wind turbine blades in the production

Lyngby, Rasmus Ahrenkiel; Nielsen, Ewa; De Chiffre, Leonardo; Aanæs, Henrik; Dahl, Anders Bjorholm

Published in:
Precision Engineering

Link to article, DOI:
[10.1016/j.precisioneng.2018.12.006](https://doi.org/10.1016/j.precisioneng.2018.12.006)

Publication date:
2019

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Lyngby, R. A., Nielsen, E., De Chiffre, L., Aanæs, H., & Dahl, A. B. (2019). Development and metrological validation of a new automated scanner system for freeform measurements on wind turbine blades in the production. *Precision Engineering*, 56, 255-266. <https://doi.org/10.1016/j.precisioneng.2018.12.006>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Development and Metrological Validation of a New Automated Scanner System for Freeform Measurements on Wind Turbine Blades in the Production

Rasmus Ahrenkiel Lyngby^{a,b,*}, Ewa Nielsen^b, Leonardo De Chiffre^c, Henrik Aanæs^a, Anders Bjorholm Dahl^a

^a*Department of Applied Mathematics and Computer Science, the Technical University of Denmark, Richard Petersens Plads, Building 324, 2800 Kgs. Lyngby, DK*

^b*Siemens Gamesa Renewable Energy, Assensvej 11, 9220 Aalborg Øst, DK*

^c*Department of Mechanical Engineering, the Technical University of Denmark, Nils Koppels Allé, Building 404, 2800 Kgs. Lyngby, DK*

Abstract

Geometrical defects on the surface of wind turbine blades can severely degrade the blade during operation and lead to reduced lift, which in turn reduces the power output of the turbine. This paper presents an automated surface geometry inspection system which is designed based on manufacturing requirements. Estimating the measurement uncertainty and establishing traceability is difficult for huge, freeform objects. An approach based on the Modular Freeform Gauge (MFG) method is presented and used to estimate the measurement uncertainty of the system. An expanded measurement uncertainty of 665 μm ($k=2$) was established for the system and documented to be 850 μm for freeform measurements on a 55 meter long blade.

Keywords: 3D measurement, Freeform surface metrology, Large object metrology, Wind turbine blade, Modular Freeform Gauge, ISO 15530-3

1. Introduction

Surface defects on a wind turbine blade can significantly lower the blade's lift and thus the power output of the turbine [1]. This paper presents a method for creating a dense 3D model of a wind turbine blade's surface, which can be used for surface quality inspection during production. Moreover, such a surface model is a step towards creating a digital blade twin, which is a prerequisite for efficient, modern manufacturing [2] and quality control [3]. Our proposed scanner system is illustrated in Figure 1.

*Corresponding author. Tel.: +45 4525 3407

Email address: raly@dtu.dk (Rasmus Ahrenkiel Lyngby)

URL: www.dtu.dk (Rasmus Ahrenkiel Lyngby)

Figure 1: Drawing of the proposed scanner system. A structured light based 3D scanner captures sub-scans of the wind turbine blade surface while a laser based six Degrees-of-Freedom (DoF) positioning system records the positions of the individual sub-scans.

10 1.1. Wind turbine blade manufacturing and geometrical quality control

The outer geometry of a wind turbine blade is carefully designed such that the shape of its airfoil optimizes lift while reducing drag within the designated wind speed range. Every step in the production from packing of fiberglass into the mold to final surface treatment can potentially introduce surface defects.

15 The approximately cylindrical shaped part of the blade, which hits the wind first, is called the leading edge. The leading edge is the most critical zone of the airfoil because it "carves" the air. The maximum lift on the blade is attained when the airflow around the airfoil is laminar. Small-scale defects, such as pinholes, cracks or steps, can cause prematurely breakage of laminar flow, in

20 the boundary layer around the airfoil, which causes increased drag and can lead to damaging surface erosion [4, 5]. When the blade is turning, the tangential velocity of a point on the blade's surface is proportional to the distance from that point to the turbine's hub. For current blades, the velocity at which surface related defects become significant is attained from about two thirds of the blades length and onward. For a 75 meter long blade, this corresponds to the

25 last 25 meters.

Today, manufactures rely on trained experts and manual inspections to detect surface defects. While this method provides decent sensitivity, it is rather

30 slow, relatively expensive and does in many circumstances not provide quantitative measurements.

Previous research has made significant contributions towards developing an accurate and fine grained quantitative measurement method, for measuring huge

freeform components, which is suitable for automation [6, 7]. However, it seems
35 that none of these methods have been demonstrated to work on life-sized off-
shore wind turbine blades. The lack of established standards related to huge
free form components has resulted in poor documentation of their measure-
ment uncertainties. This paper presents an automated method for measuring
the leading edge geometry, which surpasses manual inspection in speed and
40 quantifiability, while retaining good sensitivity. Traceability, as defined in the
International Vocabulary of Metrology (VIM) [8] and following the Guide to
the Expression of Uncertainty in Measurement (GUM) [9], is established by an
approach based on a combination of the Procedure for Uncertainty Management
(PUMA) method, described in ISO 14253-2 [10], the modular free form gauge
45 (MFG) method [11], which is based on the substitution method defined in ISO
15530-3 [12], and reverse engineering [13].

2. The new scanner system

Modern blades for offshore turbines are huge and flexible structures with
the biggest currently extending past 80 meters in length. The blade surface is
50 double curved but with a much higher curvature in the transverse direction than
in the longitudinal direction. These two properties makes it a subject of large
scale, freeform metrology as described by Savio et al. [14]. Peggs et al. [15],
Franceschini et al. [16] and Schmitt et al. [17] agree that large scale metrology
continues to pose challenges, especially with regards to standards and uncer-
55 tainty estimation, but that a recent increase in interest and research has made
it more readily available. The difficulties often arise due to the size of the mea-
surement volume, combined with the measurement precision requirements and
workpiece deformation under the influence of gravity.

Several investigations towards dense geometry measurements of wind tur-
60 bine blades have recently been made. Fu et al. [18] used two sled-mounted
laser line scanners to measure surface deformations on a small household blade.
Petryna et al. [19] measured a small industrial blade with a system composed
of a structured light based 3D scanner, an industrial robot and a linear robot
transport unit. Shmueli et al. [20] employed photogrammetry to measure lo-
65 cal deformations in the trailing edge of wind turbine blades. Talbot et al. [21]
measured a blade-like artifact using coherent laser radar. While all of these
contributions provided valuable insight, none of them produced a scanner sys-
tem which had the resolution, the speed and the flexibility required by modern
blade manufacturing. The scanner system presented in this paper is based on
70 the lessons learned from the studies outlined above, but with a greater focus on
manufacturer requirements.

Current offshore blades rotate with tip speeds around 300 km/h. At that
speed, the smallest significant geometrical defects has a spatial extent of about
200 μm . This sets a base target for the distance between neighboring measure-
ment points and their associated measurement uncertainty. Laser based scanner

systems are highly accurate but require a relatively long time to densely measure large scale structures [6] and would likely require more than a full shift (8 hours) to measure the full leading edge on a blade. Due to the production frequency and takt times, a maximum inspection time of a quarter of a shift (two hours) seems to be the upper limit allowed by manufacturers. Structured light based scanners can achieve uncertainties down to about 100 μm while covering a 300×300 mm area with a point density of 25 points per mm^2 (equivalent to a point-to-point distance of 200 μm) or better [22]. This type of scanner has to be moved many times in order to measure the entire surface. The maximum permissible reconstruction time per sub-scan can be computed by:

$$t_{\text{mpr}} = \frac{(t_{\text{mpm}} - t_{\text{set}})A_{\text{m}}(1 - Q)}{A_{\text{s}}} - t_{\text{han}} \quad (1)$$

where t_{mpm} is the maximum permissible measurement time, t_{set} is the initial setup time, A_{m} is the measurement area covered by each sub-scan, Q is the overlap ratio between neighboring sub-scans, A_{s} is the area of the critical part of the blade surface and t_{han} is the time it takes to handle and move the scanner between locations.

The advantages of commercially available standard components, over custom build ones, are support, scalability and cost. Therefore, standard components were used as much as possible.

When selecting the best suited 3D scanner, the most important factors are speed, precision, resolution, robustness and price. To select the best one, a benchmark of current commercially available 3D scanners were performed and the RapidScan from Automated Precision Inc. (API) was chosen. It employs an unstructured light pattern [23], where two cameras capture images of a random dot pattern which is projected onto the surface. The acquisition takes roughly 2.7 seconds to finish and the subsequent reconstruction of 3D points takes about 2.3 seconds. The point-to-point spacing ranges from 220 μm nearest to the scanner and up to 350 μm furthest away in its depth of field. The depth of field extends from 245 mm to 400 mm. With about 1,100,000 points per scan at best, it covers an area of roughly 300×300 mm. The use of infrared light makes the scanner very robust against ambient illumination, as long as that lighting is constant during pattern projection, which avoids the need for screening away lights sources present in the production environment. Finally, it is reasonably priced compared to competing industrial scanners.

To measure the blade, the scanner system must be moved around the blade in all directions [19]. Due to the length of the blade, it is not possible to scan it from one position. Using a rail system is inconvenient because it limits the flexibility of the system, and instead a self-driving platform was chosen that can easily be set up at any factory floor.

The self-driving platform is constructed from hollow steel sections. It has a footprint of 1.7×1.2 meters and a height over the floor of just 200 mm. This

105 relatively flat footprint, combined with a total assembly weight of more than 600 kg, makes it a very stable platform, which effectively dampens vibrations induced by the robot. In addition, its low profile makes it ideal for crawling under the blade, even in positions with low clearance between the leading edge and the floor. The robot is mounted at an angle of 45° relative to the platform
 110 such that its primary region of singularities are tilted backwards away from the measuring region. A rectangular hole placed right below the robot's base allows the elbow joint to sweep closely over the floor, which further enhances its ability to navigate in tight spaces.

115 A Universal Robots UR10 industrial robot with six Degree of Freedom (DoF) is used due to its low weight, adequate carrying capacity, easy control and low cost. Further, it can be made ISO 15066 [24] compliant, which means that it can be operated as a collaborative robot that does not need a safety cage. This is in line with the manufacture requirement of minimizing changes to the
 120 current production environment. The robot moves the 3D scanner in a series of U-shaped trajectories around the leading edge with a number of stops to allow the scanner to measure. The trajectory is illustrated in Figure 2. Whenever the robot reaches the end of its work envelope, the platform moves forward in the direction of the leading edge and then the robot continues on its trajectory.

Figure 2: Illustration of the trajectory which is covered by the scanner on the blade surface through movements of the robot and platform. The vector $\mathbf{v}_{\text{view}}$ indicates the scanner's position relative to the surface and is aimed at a length $\|\mathbf{v}_{\text{view}}\| \approx 300$ mm.

125 The system's control loop moves the robot and platform based solely on

the measured surface geometry and a set of predefined parameters. A global positioning and tracking system is therefore not required for controlling the scan sequence. However, each sub-scan has to be transformed into a global reference frame with a precision which is on par with the scanner precision. The
130 OmniTrack II laser tracker and vProbe active target from API was selected over the others that were benchmarked. The vProbe reflects the tracker's laser beam, such that the tracker can measure x , y and z positions, but it also uses an in-build camera sensor to observe the incident angles of the beam, into the reflector, which it uses to compute its pitch and yaw orientation. The roll is provided by
135 a gyroscope. In combination, this system measures six DoF positions. Other trackers often rely on a 3D artifact, which has to be pose estimated through observations made with a camera, in order to measure orientation. Available camera resolutions seem to limit the range of such system below that which is needed. Using an active target, such as the vProbe, six DoF positions can be
140 obtained without the need of measuring four distinct passive targets, known as spherical mounted reflectors (SMRs). The position uncertainty of the vProbe is $55 \mu\text{m}$ within 7 meters, $100 \mu\text{m}$ from 7 to 15 meters and $30 \mu\text{m} + 5 \mu\text{m}/\text{m}$ from 15 to 80 meters. Occlusions between the laser tracker and the scanner is avoided by placing the laser tracker in front of the scanner system, near the
145 blade tip. The probe is rigidly mounted close to the scanner. In this setup, the tracker defines the common global reference frame.

In theory, the tracking could have been done by dead reckoning. Each robot movement is governed by a relative transformation $\mathbf{T}_{i,i+1}$ which moves it from position i to position $i + 1$. A sub-scan at position i could be transformed into
150 a global reference frame, defined by the initial robot position, by the combined transformation $\mathbf{T}_i = \mathbf{T}_{1,2}^{-1} \mathbf{T}_{2,1}^{-1} \dots \mathbf{T}_{i-1,i}^{-1}$. However, dead reckoning accumulates small errors, which relatively quickly leads to a significant positioning uncertainty. Other means of tracking, such as the Nikon iGPS radio based system, was also considered, but they generally either required mounting fixed "satel-
155 lites" around the measurement area or could not deliver the required precision.

A photograph of the scanner system in action is shown in Figure 3.

2.1. Controlling the scan sequence

Before describing the control loop, it is necessary to have an estimate of how
160 much time is available for each sub-scan. Manufactures are keen on limiting inspection times as much as possible, but they generally seem content if the geometrical inspection can be conducted within two hours. As explained previously, only the outer third of the blade is inspected, which amounts to 25 m for an off-shore blade. In a realistic setting, it would probably be enough to measure
165 0.5 m up on both sides of the leading edge. Some overlap between sub-scans is preferable, and 20% of the scan width could be a reasonably number. Given that 20 minutes are needed for setting up the measurement system, Equation 1 gives a maximum permissible sub-scan and movement time of 17.3 s. The scanner takes 2.7 seconds to acquire the necessary images and then 2.3 seconds to
170 reconstruct 3D surface points from the images. The reconstruction can take

Figure 3: Photograph of the scanner system in action. The 3D scanner is encapsulated in a black and yellow striped protective cage and the robot is covered by a tight fabric tube to protect its joints and motors from dust. The laser tracker with its green "on"-LED, standing 20 meters away, can be glimpsed in the middle towards the photo's right edge.

place while the scanner moves, which leaves $17.3 - 2.7 = 14.6$ seconds for movement. This example, which uses realistic values, gives an idea of how much time can be spend on moving the scanner. While it might be feasible to manually move the scanner, there are multiple benefits gained by automating the process. Schubel [25] showed that automation, in general, reduces blade manufacturing costs. The movement can be completed significantly faster by automating the scan sequence, which can reduce the total inspection time significantly, with cost savings in return.

The control loop is designed such that it does not rely on any kind of CAD model. It only requires specifying certain parameters such as the number of sub-scans per U-curve, length of the U-curve and overlap between scans from neighboring U-curves. Avoiding a dependency of CAD model eases the usability of the system when different kinds of blade types have to be inspected. Moreover, a pre-computed path would somehow have to be aligned to the physical blade, which is difficult due to the gravity induced blade deformation mentioned previously. Instead of using pre-computed robot positions, the scanner system computes the positions as it goes. It plans its next movement based on the just acquired surface scans, why no direct alignment between measurements and design model is necessary.

A block diagram of the control loop is illustrated in Figure 4. The path planner sends a translation vector, $\mathbf{t}$, to the platform and a sequence of N acquisition positions, $(\mathbf{T}_i)_{i=1}^N$, to the robot. The platform adjust its bearing and

then drives along the translation vector. When finished, it triggers the robot
 195 which then begins moving on its sequence. For every position, $\mathbf{T}_i$, the robot
 stops and trigger the scanner which measures the surface. Once the scanner
 finishes its acquisition, it triggers the robot which moves to the next position
 in the sequence. When the last position is reached, the scanner sends the N
 resulting scans, $(\mathbf{P}_i)_{i=1}^N$, back to the path planner, which then uses them to
 200 compute the next sequence of acquisition positions. The loop stops once the
 blade tip has been scanned.

Figure 4: Illustration of the scanner system's control loop. $\mathbf{t} \in \mathbb{R}^2$ is a translation vector in the 2D plane constituted by the floor. $(\mathbf{T}_i)_{i=1}^N$ is a sequence of N six DoF robot poses, with $\mathbf{T}_i \in \mathbb{R}^{4 \times 4} \forall i$. $(\mathbf{P}_i)_{i=1}^N$ is a sequence of N resulting point clouds corresponding to the N robot positions.

3. Traceability

The establishment of traceability for the measurement data obtained using
 the scanner system was performed through a comparison with freeform mea-
 205 surements using a tactile coordinate measuring machine (CMM). The approach
 follows the general guidelines in the GUM [9, 10]. However, a more specific
 evaluation procedure has to be followed as the GUM is not directly applicable
 to the more complex measurement task specified in this paper.

Here, a method is presented which is based on the MFG method [11] derived
 210 from the substitution method described in ISO 15530-3 [12].

Particular care was given to the leading edge which is the most crucial part
 of the blade. It can be well approximated by a 100 mm cylinder for blades with
 a length between 40 and 80 meters. The low curvature regions before and after
 the leading edge could be well approximated by a section of a cylinder with an
 215 approximate diameter of 1200 mm. This is illustrated in Figure 5. Here, focus
 is on the leading edge, which is the reason why an MFG containing only the
 small cylinder is chosen.

Figure 5: Profile view of the cylinders needed to approximate a 55 meter wind turbine blade by an MFG. The dashed orange circle illustrates a cylinder with a 100 mm diameter. The dashed blue circle arc illustrates part of a cylinder with a 1,200 mm diameter. The black curve illustrates the leading edge together with the top and bottom sides of the blade profile.

The traceability chain for the blade measurements acquired by the scanner system is illustrated in Figure 6.

Figure 6: Illustration of the traceability chain. Symbols refer to the text.

Because the MFG consists of only one single object, it is not necessary to calibrate the MFG configuration. Following Savio and De Chiffre [11], the uncertainty contributions of the cylinder's local deviation are illustrated in Table 1. Here, U_{CYL} is the uncertainty assigned to local radius deviations, which is defined as the distance between the "calibrated" CAD model and a point measured on the objects surface, in the direction of the surface normal. The term "calibrated" CAD model is defined by Savio and De Chiffre [11], and for our application it is a cylinder with a diameter that corresponds to the cylinders diameter as stated in its calibration certificate [26]. U_{CYL} is a combination of several contributions [11]. The uncertainty of the cylinder's radius is represented by u_{rCYL} which is equal to half of the uncertainty of the diameter from the cer-

tificate. The unknown systematic effect of form error on the local deviation is represented by u_{ufCYL} and follows a triangular distribution. This is why its standard deviation has to be multiplied by a factor of $1/\sqrt{6}$ when combining it with the other, normally distributed, distributions [9]. It is further divided
235 by 2 because the certificate states the error in terms of the cylinder diameter and not the radius. The uncertainty stemming from the assessment of the form error is given by u_{fCYL} , and is given by half of the uncertainty of the form error from the certificate, because the form error from the cylinder certificate is given with respect to diameter instead of radius. Even though the contribution
240 of the MFG on the final uncertainty of the blade measurements is expected to be small, they are included following Savio and De Chiffre [11] for completeness.

An expanded measurement uncertainty can be assigned to the CMM when used for freeform measurements, labeled U_{CMM} , from a combination of repeated
245 profile measurements of the cylinder, u_{repCYL} , the cylinder's calibration, u_{CYL} , and a contribution coming from thermal effects, also known as environmental effects, if the repeated measurements are not conducted at 20°C, u_{eCYL} . This is illustrated in Table 2.

The substitution method is used to transfer traceability from the tactile
250 CMM to the optical scanner system through a calibrated workpiece. It is not possible to measure an entire blade in the CMM due to its size and the limited reach of the CMM and this is the reason to use a smaller workpiece which contains the leading edge. Such a workpiece can be fabricated by cutting out a
255 section from an actual blade which will fit in the CMM. The piece was chosen such, that the diameter of the half-cylinder formed by its leading edge is within 25 mm of the diameter of the calibration cylinder as required by ISO 15530-3:2011 [12]. The geometry of the leading edge is relatively uniform when seen over the inspection blade region. It is thus within the 10% geometrical deviation
260 allowed by ISO 15530-3:2011 [12].

The workpiece is calibrated through a series of repeated profile measurements, given by u_{repCW} , while taken the uncertainty of the CMM, u_{CMM} , and environmental effects, u_{eCW} , into account. The expanded uncertainty is labeled U_{CW} and defined in Table 3.

The uncertainty of the calibrated workpiece is transferred to the scanner system through repeated scans of the workpiece with the system. A series of repeated measurements with different distances to the laser tracker is acquired in order to investigate the relation between this distance and the measurement
270 uncertainty. The uncertainty is labeled U_{SS} and defined in Table 4. As the workpiece measurements with the scanner system take place in the production environment and the CMM measurements take place in a laboratory, the workpiece is the link between the laboratory acquired measurements and the production acquired measurements.

275 Finally, the uncertainty of the blade measurements, U_{WTB} , is estimated

through a series of repeated blade scans. This uncertainty is defined in Table 5. Notation follows the GUM, where type A standard uncertainties are estimated from sampled distributions, and type B are given from a priori distributions.

Table 1: Uncertainty contributions on the MFG cylinder (CYL) (adapted from [11]).

Uncertainty Component	Symbol	Type	Estimation
Uncertainty of radius	u_{rCYL}	B	Half of diameter uncertainty from certificate
Unknown effect of form error	u_{ufCYL}	B	$\frac{1}{\sqrt{6}} \frac{\text{Form error}}{2}$
Uncertainty of form	u_{fCYL}	B	Half of form uncertainty from certificate

$$U_{CYL} = k\sqrt{u_{rCYL}^2 + u_{ufCYL}^2 + u_{fCYL}^2}$$

Table 2: Uncertainty budget for CMM measurements on MFG cylinder (CYL).

Uncertainty Component	Symbol	Type	Estimation
Calibration uncertainty of MFG cylinder	u_{CYL}	B	From Table 1
Repeatability	u_{repCYL}	A	Repeated CMM measurements on MFG cylinder
Temperature	u_{eCYL}	B	U-shaped distribution

$$U_{CMM} = k\sqrt{u_{CYL}^2 + u_{repCYL}^2 + u_{eCYL}^2}$$

Table 3: Uncertainty budget for CMM measurements on calibrated workpiece (CW).

Uncertainty Component	Symbol	Type	Estimation
Uncertainty of CMM measurements	u_{CMM}	B	From Table 2
Repeatability	u_{repCW}	A	Repeated CMM measurements on CW
Temperature	u_{eCW}	B	U-shaped distribution

$$U_{CW} = k\sqrt{u_{CMM}^2 + u_{repCW}^2 + u_{eCW}^2}$$

Table 4: Uncertainty budget for measurements with the optical scanner system (SS) on calibrated workpiece (CW).

Uncertainty Component	Symbol	Type	Estimation
Uncertainty of CMM measurements on CW	u_{CW}	B	From Table 3
Repeatability	u_{repSS}	A	Repeated SS measurements on CW
Temperature	u_{eSS}	B	U-shaped distribution
$U_{SS} = k\sqrt{u_{CW}^2 + u_{repSS}^2 + u_{eSS}^2}$			

Table 5: Uncertainty budget for measurements with the optical scanner system (SS) on wind turbine blade (WTB).

Uncertainty Component	Symbol	Type	Estimation
Uncertainty of optical measurements on CW	u_{SS}	B	From Table 4
Repeatability	u_{repWTB}	A	Repeated SS measurements on WTB
Temperature	u_{eWTB}	B	U-shaped distribution
$U_{WTB} = k\sqrt{u_{SS}^2 + u_{repWTB}^2 + u_{eWTB}^2}$			

280 4. Experimental investigation

The measurements needed for estimating the uncertainties were acquired in four distinct sessions. The calibration of the MFG cylinder is described by Savio [26]. The CMM was calibrated by measuring the MFG cylinder. The CMM was then used to calibrate the workpiece. The workpiece was measured by the
285 scanner system in a way which best simulated the actual blade measurement process. Finally, an actual blade was measured with the scanner system and used to assign a final measurement uncertainty to the freeform measurements of the blade.

4.1. Experimental setup

290 A Zeiss OMC 850 tactile CMM, with a Maximum Permissible Error in space of $MPE_{U3} = (3 + L/250) \mu m$ (L in mm) and a probe force of 0.2 N, was used for all CMM measurements. It was operated through the Zeiss Calypso software. The stylus system was chosen such that the tip was able to reach points well underneath the downwards facing side of the cylinder. This was achieved by
295 selecting a 180 mm long stylus with a 8 mm diameter ruby sphere. The CMM was placed in a temperature controlled room where the temperature is $21 \pm 1^\circ C$.

The used MFG was a 360 mm long steel test cylinder with a calibrated diameter of 100.0112 mm with an expanded measurement uncertainty of $0.4 \mu\text{m}$ ($k=2$) and a $1.0 \mu\text{m}$ cylindricity calibrated with an expanded measurement uncertainty of $0.5 \mu\text{m}$ ($k=2$) [26]. Here, k is the coverage factor, as defined by the GUM, which is multiplied onto the standard uncertainty. A coverage factor of 2 implies that all values within two times the standard deviation from the mean is retained inside the expanded uncertainty, which corresponds to 95% of the possible values.

A workpiece which imitates the leading edge was fabricated by cutting a 600×750 mm section out of the leading edge of a real blade. Four 25.4 mm reference spheres were mounted on the workpiece near the leading edge to be used for alignment in the CMM as well as scanner.

4.2. Calibration of CMM

The cylinder was placed in the CMM and supported by two V-blocks as shown in Figure 7. After having fixed the cylinder to the CMM's table, the setup was allowed to acclimatize. The stylus system was qualified using a reference sphere placed next to the cylinder. The cylinder was aligned through a plane measured on its top and a point defined as the center of a circle traced around the middle of the cylinder.

Figure 7: Photograph of the CMM measuring process of the reference MFG cylinder showing the probe near the cylinder's top.

Five profile curves were programmed using the cylinder's CAD model, as seen in Figure 8, with each of the profiles repeated five times. The profiles spanned 180° of a circle arc and were placed at 90 mm, 135 mm, 180 mm,

225 mm and 270 mm from the cylinder's top. 52 measuring points were evenly distributed on each of the profile curves. The measurements were conducted as individual point measurements in free-form mode, which allowed the CMM to save the 3D coordinates of the measured points. Due to a period of exceptionally
 325 warm weather in Denmark, the temperature control struggled immensely, why the temperature varied between 24.0°C and 25.1°C during the measurements. A systematic correction for temperature was applied to the measurements.

Figure 8: Plot of the measuring points on the profile curves together with a section of the cylinder CAD model.

The standard deviation of the repeated measurements was estimated by fitting a mathematical cylinder to the measurements. The signed distance between
 330 each of the measured points and the surface of the mathematical cylinder was computed using Calypso. The standard deviation of these distances was used to estimate the measurement uncertainty u_{repCYL} in Table 2.

4.3. Calibration of calibrated workpiece

The workpiece was mounted in the CMM such that the leading edge was
 335 nearly parallel to the CMM's Y-axis at approximately the same location as the cylinder. Three rods with spherical ends provided a stable nest for the workpiece, preventing it from tilting. The rods also lifted the workpiece up over

the CMM's measurement table, which allowed the stylus to reach around the leading edge and measure points on a curve starting underneath the bottom of the workpiece and extending up on its top. A beam was mounted through the workpiece in the transverse direction and used to fix it to the table. Through expert assessment, it was sought to fasten the workpiece tight enough to withstand the force of the CMM stylus, but not so tight that it would deform. The arrangement is shown in Figure 9. The black and white circular stickers, seen on the figure, were added for a separate investigation with a commercial scanner, not reported here. The stickers were placed such that they did not interfere with the CMM measurements.

Figure 9: Photograph of the calibrated workpiece mounted in the CMM. The black and white stickers were used for a separate investigation, which is not reported here.

The workpiece was measured through a set of perpendicular curves. The curves were planned by manually measuring the start and end point of each curve with the CMM and then let the CMM automatically trace out the rest of the curve by "feeling its way forward". It did so by moving in circles in the direction from the start point towards the end point. Whenever it hit the surface, it measured the position and started a new circular motion. This process was repeated until the end point was within a threshold distance of 15 mm. A circle radius of 15 mm was chosen, which resulted in 36 points on each curve. The curves were placed with a spacing of 40 mm. The length of the workpiece would have allowed for 14 curves had it not been for the four spheres which shadowed three curves, thus yielding a total of 11 curves.

After mounting and planning, the workpiece was cleaned and allowed to

360 acclimatize. The stylus system was qualified as done before the cylinder mea-
 surements. Five points were measured on each of the two top spheres and then
 six points on one of the bottom spheres. The bottom sphere was difficult to reach
 and thus six points were needed to measure it properly. Three mathematical
 spheres were fitted to the measurements and the positions of their centers were
 365 used to form a reference plane. The CMM then executed the measurement pro-
 gram which consisted of five repetitions of the $36 \cdot 11 = 396$ semi-automatically
 defined points.

The temperature varied between 23.5°C and 25°C during the measurements.
 Fiberglass and epoxy composites have a Coefficient of Thermal Expansion (CTE)
 370 of $\alpha_t = 54.8 + 0.163T \text{ } \mu\text{m}/^\circ\text{C}/\text{m}$ in the direction running across the fibers, and
 $\alpha_l = 14.8 + 0.039T \text{ } \mu\text{m}/^\circ\text{C}/\text{m}$ in the direction running along the the fibres,
 both with an uncertainty of 3% of the value [27]. T is the temperature and
 defined within $T \in [20, 70]^\circ\text{C}$. Taking the uncertainty contribution from ther-
 mal expansion into account is not trivial for freeform objects. The geometrical
 375 shape and internal structure of the object will lead to non-uniform deformations
 where different parts of the surface will increase or decrease in size differently.
 The behavior can be accurately estimated either through computer modeling or
 through repeated measurements of the object at different temperatures. Such
 a comprehensive estimation is often a contribution in its own right, which is
 380 the reason why it is out of the scope of the traceability estimation done here.
 Instead, a simpler approach is chosen which assigns a realistic, but potentially
 high, thermal uncertainty contribution. Looking on the blade profile, the lead-
 ing edge forms a C-shaped arc which encloses a cavity. On the workpiece, the
 arc length of the leading edge is 135 cm (rounded up to the nearest 5 cm). While
 385 the thickness of the shell varies, it is at least 20 times smaller than its length.
 Using a mean temperature of 24.25°C , the CTE of a rod made of transverse
 fibers with the same length as the leading edge is $(54.8 + 0.163 \cdot 24.25) = 58.75$
 $\mu\text{m}/^\circ\text{C}/\text{m}$. This would expand the rod by $58.75(24.25 - 20)1.35 = 337.09 \text{ } \mu\text{m}$
 with an uncertainty of $(24.25 - 20)(58.75 \cdot 0.03)1.35 = 10.11 \text{ } \mu\text{m}$. This uncer-
 390 tainty can be seen as an upper bound of the environmental contribution to the
 uncertainty of the CMM measurements, u_{eCW} , as the CTE of parallel fibers is
 much lower.

It was not possible to establish the exact location from where on the blade the
 workpiece was cut. Therefore, a model of the workpiece could not be made from
 the blade's CAD model. Instead, it had to be reverse engineered from the CMM
 measurements. This was done by fitting a Bézier surface to the measured points.
 First, the bias between the mean positions of the five repeated measurement sets
 was reduced by applying the Iterative Closest Point (ICP) algorithm [28]. Then,
 the mean position of the five repetitions were computed at each measured point.
 Let $(\mathbf{P}^{(i)})_{i=1}^5$ be a sequence of the five repetitions of the measured points, with
 $\mathbf{P}^{(i)} \in \mathbb{R}^{396 \times 3} \forall i = 1, \dots, 5$. From this sequence, the mean positions between
 the five repetitions at each measurement point were computed and arranged into
 a matrix $\mathbf{Q} \in \mathbb{R}^{396 \times 3}$ with each row computed as $\mathbf{q}_j = 1/5 \sum_{i=1}^5 \mathbf{p}_j^{(i)}$ where $\mathbf{q}_j$

and $\mathbf{p}_j^{(i)}$ are the vectors corresponding to the j 'th row of $\mathbf{Q}$ and $\mathbf{P}^{(i)}$, respectively. The Bézier surface, $\mathbf{s}(u, v) : \mathbb{R}^2 \mapsto \mathbb{R}^3$, is defined as the outer product between two Bézier curves:

$$\mathbf{s}(u, v) = \sum_{i=0}^{d_u} \sum_{j=0}^{d_v} b_{i,d_u}(u) b_{j,d_v}(v) \mathbf{k}_{i,j}, \quad (2)$$

where $u, v \in [0, 1]$ spans a unit square plane, and defines the relative position on the surface. The functions $b_{i,d_u}(u), b_{j,d_v}(v) : \mathbb{R} \mapsto \mathbb{R}$ are Bernstein polynomials given by $b_{i,d_u}(u) = \binom{d_u}{i} u^i (1-u)^{d_u-i}$ and $b_{j,d_v}(v) = \binom{d_v}{j} v^j (1-v)^{d_v-j}$. The vectors $\mathbf{k}_{i,j} \in \mathbb{R}^3 \forall i = 0, \dots, d_u, j = 0, \dots, d_v$ are control points in 3D space. The degree of the Bézier surface is defined as (d_u, d_v) and specifies the number of control points as $(d_u + 1)(d_v + 1)$ in the u and v direction, respectively. The surface is fitted to the measurement means through least squares optimization by minimizing the following:

$$K = \arg \min_K \sum_{i=1}^N \|\mathbf{s}_K(u_i, v_i) - \mathbf{q}_i\|^2 \quad (3)$$

where $\mathbf{s}_K(u_i, v_i)$ is the predicted point on the Bézier surface, with control point sequence $K = (\mathbf{k}_{i,j})_{i=0, j=0}^{d_u, d_v}$, that corresponds to measurement mean point $\mathbf{q}_i$ with surface position (u_i, v_i) . The positions of the control points were initially laid out in a grid on a flat plane which spanned the first two principal components of $\mathbf{Q}$.

The surface fitting procedure requires that a forth running pair of (u, v) parametric coordinates are assigned to each point, which can be difficult to get exactly right. The coordinates were initialized such that u indicated which curve the points was on, with 0 corresponding to the first curve and 1 corresponding to the 11'th curve, and v indicated the location of the point on the curve with 0 corresponding to the top most point and 1 corresponding to the bottom most point. This did, however, introduce an error because of the three missing curves which was shadowed by the spheres. The distance between the curves were thus not identical, and therefore it was necessary to also optimize for the (u, v) coordinates, which was done as follows:

$$\mathbf{u}, \mathbf{v} = \arg \min_{\mathbf{u}, \mathbf{v}} \sum_{i=1}^N \|\mathbf{s}_K(u_i, v_i) - \mathbf{q}_i\|^2 \quad (4)$$

where the set of control points, K , had been optimized through Equation 3. It was found that alternating between optimizing for the positions of the control points and optimizing for the (u, v) coordinates yielded a much better surface than simply optimizing once for each. Therefore, Equation 3 and Equation 4 were applied iteratively until convergence, which happened after roughly 10 iterations. An example of the fitted surface is showed in Figure 10. Note that

405 the number of target points were $N = 11 \cdot 36 = 396$.

Figure 10: Illustration of the points measured by the CMM on the workpiece together with the fitted Bézier surface. Each point is actually a tight cluster of the five repetitions.

The standard deviation of the signed distance from all $5 \cdot 11 \cdot 36 = 1980$ measured points to the best fit Bézier surface was used to compute the uncertainty of the workpiece.

410 4.4. Calibration of the scanner system

The now calibrated workpiece was moved to the blade production site and suspended from a forklift with the leading edge oriented towards the floor. Its height over the floor was set such that it best simulated the height of the leading edge as it would have been on an actual blade positioned for measurements. The arrangement is shown in Figure 11.

Figure 11: Photograph of the scanner system measurement process of the calibrated workpiece.

The surface of the calibrated workpiece was cleaned and then allowed to acclimatize. The laser tracker was qualified through repeated measurements of a spherically mounted reflector following the specifications from the manufacturer, and the transformation between the RapidScan and the vProbe was calibrated.

420 The position of the calibrated workpiece was detected and aligned to the scanner system's coordinate frame by measuring its leading edge directly underneath with the scanner pointing straight up. Then, the path planner was used to compute two u-shaped robot trajectories, one forward and one backwards, each with six acquisition positions which were distributed such that the entire intermediate surface was covered. The arclength of each path was 840 mm. The 12 scans were repeated 10 times. In order to investigate if the scanner system's uncertainty was correlated with the distance to the laser tracker, the entire arrangement with scanner system, workpiece and forklift was brought closer to the tracker and the entire process was repeated. The workpiece was measured
430 at 12.5, 10, 7.5 and 4 meters distance. The temperature varied between 20.5°C and 21.3°C during the measurements. The environmental contribution to the uncertainty is estimated through an approach similar to that followed for the CMM measurements.

435 The point clouds resulting from the measurements were first pre-processed. Noise points situated near edges and in positions where the scanner had observed the surface at a gracing angle was removed. Then, each point cloud was transformed into the global reference frame defined by the laser tracker and combined into a single cloud for each repetition. An example is showed in
440 Figure 12.

Figure 12: The result of a single measurement of the calibrated workpiece performed by the scanner system at a distance of 12.5 meters from the laser tracker. This scan is composed of 12 individual point clouds and contains just short of 9,000,000 points. Two of the reference spheres, though sparsely sampled, are slightly visible from this angle. The colors indicate the points locations on the surface relative to the first point of the first point cloud and are added here for enhanced comprehensibility.

The distances between the repeated measurements were minimized through ICP in order to remove bias. The measurements were then aligned with the Bézier surface from the CMM measurements, which acted as a calibrated CAD model. The point clouds were roughly aligned with the surface manually and then ICP was used for fine alignment. As it was not feasible to compute the distance between the surface and all nine million points in the point cloud, a subset of points was sampled uniformly over the surface. This was done by sampling the 100 nearest neighbors around each CMM measurement position, which was annotated on the Bézier surface. The standard deviation of the point-to-surface distances was used to estimate the uncertainty of the scanner system.

4.5. Measurements of wind turbine blade

Approximately 20 meters of the leading edge of a 55 m long turbine blade were scanned with the scanner system with four repetitions. First, the blade was allowed to settle and acclimatize and the laser tracker was qualified. Except for the movement of the platform, the measurement process was identical to

the one conducted for the calibrated workpiece. The photograph in Figure 3 shows the process. Each full measurement took one hour and 20 minutes and six hours in total for the entire dataset, including handling. The temperature varied between 21.9°C and 23.5°C during the measuring session. The uncertainty contribution from the environment was estimated in a similar way to that used for the calibrated workpiece measurements, but with a leading edge arc length of 1.5 m to account for the larger maximum size of the blade.

An approach similar to the one followed for the calibrated workpiece was employed for estimating the uncertainty of the blade measurements. However, the blade CAD model could not be used directly as a reference surface due to gravity's elastic deformation of the blade. Instead, one of the repeated scans were used as a reference target, first for ridged alignment of the other scans through ICP and secondly for reconstruction of a Bézier surface. This allowed the distance between the surface and the points in the remaining scans to be computed and used for uncertainty estimation.

Though the procedure seems simple, it is complicated by the sheer number of measured points. Each repetition is made up of about 500 individual sub-scans which in turn contains roughly 800,000 points on average. Thus, each repetition contains on the order of 400,000,000 measured points. Figure 13 shows an example. The shown blade was measured in 1 hour and 15 minutes, which is well within the maximum allowed inspection time of two hours.

Figure 13: Rendering of the point cloud from a full leading edge scan. The scan is roughly 20 meters long and made up of more than 500 individual sub-scans. The total point count in the scan is over 380,000,000. A profile section is highlighted in order to provide a better feel for the geometry. The ring shaped hole seen near the tip originates from a metal lightning connector which was difficult for the scanner to acquire due to the view angle and specular highlights. Note that this is a view of the raw point set without surface reconstruction.

It was not feasible to reconstruct the entire surface, nor compute the distance between such a surface and the points, due to limits in available computing power. Instead, the problem was reduced in size by focusing on a set of sampled

locations by extracting 100 random points and then the 100 nearest neighbor points around those points as illustrated in Figure 14. Because the laser tracker and blade had been stable throughout the measurement procedure, the four repetitions were more or less aligned from the outset. This allowed for extracting all points from all repetitions inside a given cubic volume surrounding each of the randomly selected sample points. By only focusing on these small regions, it was feasible to build a k-d search tree [29, 30] for each region to be used for ICP alignment.

Figure 14: Locations of the 100 sample patches in the coordinate frame defined by the laser tracker as seen from above. The laser tracker is positioned at (0,0,0). The color of each point indicates its height on the z-axis. As seen, the points follow the contour of the blade with the tip being closest to the origin. See Figure 2 for a definition of the coordinate frame.

After the fine alignment, the 300 points closest to the centers of each cubic volume in the first repetition was found by constructing a k-d tree for each volume. A (4,4) order Bézier surface was then fitted to each of these point sets. The 100 points closest to the volume centers of the remaining three repetitions were found in a similar way and the distance between each of these points and their respective surface were computed and used for uncertainty estimation. Figure 15 shows an example of a reconstructed surface patch and an example of the repeated measurements and their respective surface from one volume is shown in Figure 16.

Figure 15: Example of Bézier surface with the 300 target points of one blade patch. The point to point distance is approximately $250 \mu\text{m}$.

Figure 16: Example of the four repeated measured points around a blade surface patch. The 100 points of each repetition is assigned a different color.

5. Results and discussion

500 This section presents the results of the uncertainty estimation method. The standard deviation of the repeated CMM measurements of the MFG cylinder was $2.7 \mu\text{m}$. Figure 17 shows the distribution of distances between the Bézier surface fitted to the mean CMM measurements and the measured CMM points. As seen, the standard deviation of the measurements $152 \mu\text{m}$, which is orders of
505 magnitude higher than that obtained through the MFG measurements. This is most likely due to the calibrated workpiece's material properties together with its size and micrometer imperfections on its surface.

Figure 17: Histogram of the deviations between the Bézier surface and the points measured on the calibrated workpiece by the CMM. The dashed orange line shows a best fit normal distribution. The histogram is based on five repetitions of 396 measurement points. Note that the notation $\mathcal{N}(\mu, \sigma)$ indicates a normal distribution with mean μ and standard deviation σ .

A histogram of the distances between the aligned surface and the extracted points from the repeated scanner measurements of the workpiece is shown in Figure 18. As with the CMM measurements, elastic deformations are expected to be a major contributor to the uncertainty. It was intended to mount the workpiece such that it best resembled an actual blade, but unfortunately this mounting could not be replicated in the CMM. As described in Section 4.3, the workpiece was lying down in the CMM instead of hanging, which meant that the force of gravity acted with a 90° rotation between the two measuring sessions. This resulted in a discrepancy between the surface model obtained from the CMM measurements and the surface which was measured by the scanner system. The scanner system measured the workpiece in 12 individual sub-scans, which was transformed into the same reference frame through the positions measured by the laser tracker system. The measurements were repeated 10 times. Uncertainties in the positioning system caused the 12 sub-scans to be positioned a little different at every repetition. Thus, the tracker system's uncertainty propagated through to the overall uncertainty of the scanner system. In addition, the camera system also generally has a larger measurement uncertainty than the CMM [31].

Figure 18: Histogram of the deviations between the Bézier surface, which was fitted to the CMM measurements, and the selected points measured on the calibrated workpiece by the scanner system.

It was speculated that there would be a correlation between the measurement uncertainty and the distance between the scanner system and the laser tracker. This was investigated by measuring the workpiece at four different distances from the tracker. A boxplot of the surface to point distances at each of the four distances is showed in Figure 19. The uncertainty of measuring the (x, y, z) positions of the active target is strongly related to the distance of the laser tracker, but the uncertainty of measuring the orientation (ψ, θ, ϕ) relates only vaguely to the distance. From the measurements conducted at different distances, it was found that there is no apparent relation between the scanner system's measurement uncertainty and the distance between the scanner and the tracker. It is expected that this is because the uncertainty of the orientation measurements is significantly higher than that of the position measurements.

Figure 20 shows a histogram of the distances between the reconstructed blade patches and the repeated measured points. The standard deviation is slightly lower than that obtained from the calibrated workpiece, but on the same order of magnitude.

Figure 19: Boxplots of the deviations between the Bézier surface and points measured by the scanner system measured at different distances from the laser tracker. There is no apparent correlation between tracker distance and the point-to-surface deviations.

Figure 20: Histogram of the point to surface deviations between the extracted blade patches from all repetitions and the fitted surfaces.

Table 6 shows the standard uncertainties estimated during the calibration procedure and the final expanded uncertainties for each measurement step. As seen, the final, rounded expanded uncertainty ($k=2$) is $850 \mu\text{m}$ on the blade measurements.

Table 6: Uncertainty estimations for the blade surface measurements (values in μm , $k=2$).

Uncertainty Component	Symbol	Uncertainty
Uncertainty of cylinder radius	u_{rCYL}	0.1
Unknown effect of form error	u_{ufCYL}	0.2
Uncertainty of form	u_{fCYL}	0.13
Expanded uncertainty for MFG	U_{CYL}	0.52
Repeated CMM measurements on CYL	u_{repCYL}	2.73
Temperature	u_{eCYL}	0.16
Expanded uncertainty for CMM	U_{CMM}	5.50
Repeated CMM measurements on CW	u_{repCW}	152.23
Temperature	u_{eCW}	10.11
Expanded uncertainty for CW	U_{CW}	305.18
Repeated SS measurements on CW	u_{repSS}	294.57
Temperature	u_{eSS}	2.12
Expanded uncertainty for SS	U_{SS}	663.50
Repeated SS measurements on WTB	u_{repWTB}	253.58
Temperature	u_{eWTB}	7.11
Expanded uncertainty for WTB	U_{WTB}	835.25

The CMM is calibrated with an uncertainty of $5.5 \mu\text{m}$, while the calibration of the workpiece with the CMM yields an uncertainty of $155 \mu\text{m}$. The workpiece is thus a major contributor to the uncertainty. It is very likely that its uncertainty can be brought down significantly by replacing the fiberglass blade-piece with one made from carbon fiber. Such a workpiece would be notably more rigid and lighter, which would make it less prone to elastic deformations. If the uncertainty of the calibrated workpiece could be lowered by a factor 10 to $30 \mu\text{m}$, the uncertainty of the scanner system would be lowered to $600 \mu\text{m}$. This would further lower the uncertainty of the blade measurements to $780 \mu\text{m}$. The scanner system would then be the primary contributor to the uncertainty, why the uncertainty could possibly be brought further down by using a better 3D scanner.

6. Conclusion

A new optical 3D system for scanning the leading edge of wind turbine blades was presented and its freeform measuring capability demonstrated on a

real blade. The scanner system was able to scan 20 meters of the tip of a 55 meter wind turbine blade in a real production environment in just 90 minutes. To the extend of our knowledge, this is the first time such a demonstration has
565 been carried out. Traceability was established through a procedure based on the MFG method and the substitution method from ISO 15530-3. Using a reference steel cylinder, a laboratory CMM was calibrated with an expanded measurement uncertainty of $5.5 \mu\text{m}$ ($k=2$). Using the CMM, a workpiece containing the leading edge of a blade was calibrated with an expanded uncertainty of $300 \mu\text{m}$.
570 The scanner system was documented to have a measurement uncertainty of $650 \mu\text{m}$ through the calibrated workpiece, and provided measurements of the blade with an expanded uncertainty of $835.25 \mu\text{m}$.

Acknowledgments

The authors would like to thank the Innovation Fund Denmark for financially
575 supporting the project through grant number 4135-00119B and Siemens Gamesa Renewable Energy A/S for providing the remaining funds. Thank to Christian Brandt Lauritzen and Peder Bent Hansen from FORCE Technology for their contributions to the construction of the scanner system. The reference CMM measurements would not have been possible without the help of Klaus Liltorp,
580 Technical University of Denmark, who we would also like to thank.

References

- [1] N. Dalili, A. Edrisy, R. Carriveau, A review of surface engineering issues critical to wind turbine performance, *Renewable and Sustainable Energy Reviews* 13 (2) (2009) 428 – 438.
- 585 [2] J. Lee, E. Lapira, B. Bagheri, H. an Kao, Recent advances and trends in predictive manufacturing systems in big data environment, *Manufacturing Letters* 1 (1) (2013) 38 – 41.
- [3] M. Germani, F. Mandorli, M. Mengoni, R. Raffaelli, CAD-based environment to bridge the gap between product design and tolerance control, *Precision Engineering* 34 (1) (2010) 7–15.
590
- [4] B. J. Holmes, C. J. Obara, L. P. Yip, Natural Laminar Flow Experiments on Modern Airplane Surfaces, NASA Technical Paper 2256.
- [5] M. H. Keegan, D. Nash, M. Stack, On erosion issues associated with the leading edge of wind turbine blades, *Journal of Physics D: Applied Physics* 46 (38) (2013) 383001.
595
- [6] S. D. Hand, D. B. Ober, B. A. Bond, E. A. Devine, Dimensional measurement of a composite ship hull using coherent laser radar yielding submillimeter results, *Journal of ship production* 20 (4) (2004) 232–239.

- 600 [7] W. Cuyppers, N. Van Gestel, A. Voet, J.-P. Kruth, J. Mingneau, P. Bleys, Optical measurement techniques for mobile and large-scale dimensional metrology, *Optics and Lasers in Engineering* 47 (3-4) (2009) 292–300.
- [8] J. C. on Guides for Metrology (JCGM), 200: 2012—International Vocabulary of Metrology—Basic and General Concepts and Associated Terms (VIM), Standard, 2012.
- 605 [9] ISO/IEC Guide 98-3:2008, Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM), Standard, International Organization for Standardization, Geneva, Switzerland, 2008.
- [10] ISO 14253-2:2011, Geometrical product specifications (GPS) – Inspection by measurement of workpieces and measuring equipment – Part 2: Guidance for the estimation of uncertainty in GPS measurement, in calibration of measuring equipment and in product verification, Standard, International Organization for Standardization, Geneva, Switzerland, 2011.
- 610 [11] E. Savio, L. De Chiffre, An artefact for traceable freeform measurements on coordinate measuring machines, *Precision Engineering* 26 (1) (2002) 58–68.
- 615 [12] ISO 15530-3:2011, Geometrical product specifications (GPS) – Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement – Part 3: Use of calibrated workpieces or measurement standards, Standard, International Organization for Standardization, Geneva, Switzerland, 2011.
- 620 [13] A. Gameros, L. De Chiffre, H. Siller, J. Hiller, G. Genta, A reverse engineering methodology for nickel alloy turbine blades with internal features, *CIRP Journal of Manufacturing Science and Technology* 9 (2015) 116–124.
- [14] E. Savio, L. De Chiffre, R. Schmitt, Metrology of freeform shaped parts, *CIRP annals* 56 (2) (2007) 810–835.
- 625 [15] G. Peggs, P. G. Maropoulos, E. Hughes, A. Forbes, S. Robson, M. Ziebart, B. Muralikrishnan, Recent developments in large-scale dimensional metrology, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* 223 (6) (2009) 571–595.
- [16] F. Franceschini, M. Galetto, D. Maisano, L. Mastrogiacomo, Large-scale dimensional metrology (LSDM): from tapes and theodolites to multi-sensor systems, *International journal of precision engineering and manufacturing* 15 (8) (2014) 1739–1758.
- 630 [17] R. Schmitt, M. Peterek, E. Morse, W. Knapp, M. Galetto, F. Härtig, G. Goch, B. Hughes, A. Forbes, W. Estler, Advances in Large-Scale Metrology—Review and future trends, *CIRP Annals-Manufacturing Technology* 65 (2) (2016) 643–665.
- 635

- [18] H.-L. Fu, K.-C. Fan, Y.-J. Huang, M.-K. Hu, Innovative optical scanning technique and device for three-dimensional full-scale measurement of wind-turbine blades, *Optical Engineering* 53 (12) (2014) 122411.
- 640 [19] Y. Petryna, A. Künzel, M. Kannenberg, Fault Detection and State Evaluation of Rotor Blades, in: EWSHM-7th European Workshop on Structural Health Monitoring, 2014.
- [20] J. Shmueli, M. A. Eder, A. Tesauero, A versatile stereo photogrammetry based technique for measuring fracture mode displacements in structures, 645 *Precision Engineering* 39 (2015) 38–46.
- [21] J. Talbot, Q. Wang, N. Brady, R. Holden, Offshore wind turbine blades measurement using Coherent Laser Radar, *Measurement* 79 (2016) 53–65.
- [22] E. R. Eiríksson, J. Wilm, D. B. Pedersen, H. Aanaes, Precision and accuracy parameters in structured light 3-D scanning, *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences* 40 650 (2016) 7.
- [23] V. Couture, N. Martin, S. Roy, Unstructured light scanning to overcome interreflections, in: *Computer Vision (ICCV)*, 2011 IEEE International Conference on, IEEE, 1895–1902, 2011.
- 655 [24] ISO/TS 15066:2016, Robots and robotic devices – Collaborative robots, Standard, International Organization for Standardization, Geneva, Switzerland, 2016.
- [25] P. Schubel, Cost modelling in polymer composite applications: Case study – Analysis of existing and automated manufacturing processes for a large 660 wind turbine blade, *Composites Part B: Engineering* 43 (3) (2012) 953 – 960.
- [26] E. Savio, Reference measurements on cylinders at the Centre for Geometrical Metrology, Report MM99.57, Department of Manufacturing Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark, 1999.
- 665 [27] D. McElroy, F. Weaver, C. Bridgman, Thermal expansion of epoxy-fiberglass composite specimens, *International Journal of Thermophysics* 9 (2) (1988) 233–243.
- [28] P. J. Besl, N. D. McKay, Method for registration of 3-D shapes, in: *Sensor Fusion IV: Control Paradigms and Data Structures*, vol. 1611, International 670 Society for Optics and Photonics, 586–607, 1992.
- [29] J. L. Bentley, Multidimensional binary search trees used for associative searching, *Communications of the ACM* 18 (9) (1975) 509–517.

- [30] F. Pedregosa, G. Varoquaux, A. Gramfort, V. Michel, B. Thirion, O. Grisel, M. Blondel, P. Prettenhofer, R. Weiss, V. Dubourg, J. Vanderplas, A. Pas-
675 sos, D. Cournapeau, M. Brucher, M. Perrot, E. Duchesnay, Scikit-learn:
Machine Learning in Python, *Journal of Machine Learning Research* 12
(2011) 2825–2830.
- [31] R. Lyngby, H. Aanæs, E. Nielsen, A. Dahl, Autonomous surface inspection
of wind turbine blades for quality assurance in production, in: EWSHM-9th
680 European Workshop on Structural Health Monitoring, BINDT, 2018.