

Interactive comment on “Establishing a robust testing approach for displacement measurement on a rotating horizontal axis wind turbine” by Nadia Najafi and Allan Vesth

Anonymous Referee #1

Received and published: 10 December 2017

General comments

The study “Establishing a robust testing approach for displacement measurement on a rotating horizontal axis wind turbine” describes the experiment on a scaled model of operating wind turbine, where the blades displacements were measured using stereo photometry. The paper describes the calibration of the measurement system and the tracking procedure: the two important operations required when applying stereo photometry to operating wind turbines.

Though the paper contains important findings and recommendations, which could be quite useful for those who considers stereo photometry, paper’s quality is not sufficiently high to recommend it for publication. A major revision is necessary.

Thank you for reconsidering the paper and constructive comments. In the following I tried to be precise in answering and satisfying the points.

** All the page numbers, reported in the answers, are based on the latest marked manuscript at the end of the document (after the responses to the reviewers).

Specific comments

English requires some polishing: some of the paragraphs are not quite clear because of the language. Generally, the paper is written sloppy, there are many unexplained statements; sometimes, no details provided. Also the paper does not provide any critical assessment of the suggested techniques. **The text has been reworked and a discussion regarding challenges with the method has been added.**

The paper claims “robust . . . measurement on a rotating . . . wind turbine”, however only demonstrates the techniques on a quite small model and does not provide any considerations regarding the scalability of the measurement system. **Considerations regarding the scalability of the measurement system have been added.**

The reference list could be updated: during the recent years quite many measurements campaigns were reported on real size operating wind turbines, and the references to campaigns from 2002 look quite outdated. **The reference list is updated:**

In page 2, line 2, I replaced two reference from 2002 with two new works in the same filed from 2017 and 2014 and also added a new reference from 2016 to be an example of damage detection via traditional transducers:

- Weijtjens, W., Verbelen, T., Capello, E., Devriendt, C. (2017): Vibration based structural health monitoring of the substructures of five offshore wind turbines, pp. 2294-2299, Procedia Engineering 199.
- Manzato, S., Santos, F., Peeters, B., LeBlanc, B., White, J. R. (2014): Combined accelerometers-strain gauges Operational Modal Analysis and application to wind turbine data, Proceedings of the 9th International Conference on Structural Dynamics: June 30-July 2, 2014, Porto, Portugal.
- Lorenzo, E. D., Petrone, G., Manzato, S., Peeters, B., Desmet, W., Marulo, F. (2016): Damage detection in wind turbine blades by using operational modal analysis, pp. 289-301, Structural Health Monitoring. 15(3).

I also provided 3 new references from 2012, 2014 and 2015 to page 2, line 4 to refer to the measurement on large structures and bridges.

- Ye, X. W., Ni, Ye. Q., Wong, K. Y., Ko, J. M. (2012): Statistical analysis of stress spectra for fatigue life assessment of steel bridges with structural health monitoring data, pp. 166–176, Engineering Structures 45.
- Xia, Z., Zhang, P., Ni, Y., Zhu, H. (2014): Deformation monitoring of a super-tall structure using real-time strain data, pp. 29–38, Engineering Structures 67.
- Siriwardane, S. C. (2015): Vibration measurement-based simple technique for damage detection of truss bridges: A case study, pp. 50–58, Case Studies in Engineering Failure Analysis 4.

Quality of the figures needs significant improvement. **The quality of Figures 1 and 5 has been improved. Figures 10-13 are also vector graphics and have a very high resolution.**

Technical corrections

P.2, line 23: should be “are”, not “is”. **It is corrected.**

P.2 line 32: using “well-defined” in this context is confusing. **I changed the phrase in the whole document to avoid the confusion: “This study is focused on establishing a ~~well-defined~~ clearly described and easily**

applicable procedure to measure displacement on the components of a rotating horizontal axis wind turbine using stereo vision technique.”

P.3 line 14: why an Envision wind turbine is mentioned? Is it important in the context? It is mentioned to provide enough information about the case study which is a scaled down Envision wind turbine. However the Envision part is removed to avoid confusion.

P.4 line 2. What is the “full resolution”? It might not be the proper phrase in this sentence therefore I changed it to “full size”.

P.4 lines 8-9. Consideration regarding the distances is very confusing. What do you mean? The sentence is rephrased to give a better understanding:

This setup satisfies the rule of thumb which says the distance between the cameras should be at least $1/3$ of the distance between the cameras and the test object; it can be up to 3 times of the distance as long as all the targets on the object can be seen in the stereo image pairs.

P. 5, line 1. How the marker shown in Fig.3 helps to avoid the mentioned difficulties? Please explain. The paragraph is revised and more explanation is added to that.

P.6 line 17. Using term “smart device” is discussable in scientific literature. Please provide what is the functionality of the device. In the following text, usage of word “Leica” is too unceremonious. “Leica” is the name of a German company, which produces many other devices. I agree with you comment, thus I removed the term “smart device” and added more explanation to the paragraph to describe Leica Nova MS50 with more details.

Fig. 5 seems to be rotated 90 degrees CCW. Why not to put it as it looks in reality? Same for fig.8. The orientation of the images is because of the camera positioning on the camera holder. To eliminate the confusion, I rotate the figures 4, 5 & 8 to be in the same orientation of the real world.

P.7, line 9. Casualty: “the rotor rotates one cycle within 40 pictures” or “the camera takes 40 pictures during one rotor revolution”? I think they both have the same meaning, but the sentence that you mentioned might be more clear, therefore I replace sentence “the rotor rotates one cycle within 40

pictures” with the sentence that you suggested: “the camera takes 40 pictures during one rotor revolution”.

P.8 line 7. Where are “the first and second point (N1)”? It is unclear from fig.6. I added the position of the first and second points to Figure 6. In addition N1 is “the number of image sequences between the first and second position of the marker” as it is explained in page 8, line 7 and also in the caption of Figure 6.

Do the terms “line of sight” (p.9, line 6) and “light ray” (p.10, line 11) refer to the same? If yes, avoid using the both terms, if not, please explain the difference. The comment is absolutely true, they refer to the same thing, thus I revised the text and used from line of sight in the document.

What does Table 1 mean? How do the numbers quantify the quality of calibration? Table 1 presents the distance between the lines of sight during rotation for one of the markers and for different calibrations. The lines of sight from the marker to the cameras do not exactly intersect in the space due to the inaccuracies and the 3D position is regarded as the point with minimum distance from two lines of sight (Trucco and Verri, 1998). Therefore the distance between the lines of sight is considered as an indication of measurement inaccuracy that is mainly caused by calibration uncertainties and light reflections and also by other environmental and physical factors. The light and other environmental factors are almost the same in all the measurements in Table 1, therefore the different values of lines of sight distances are mostly due to different calibrations.

For more clarification, more explanation is added to 3 paragraphs before Table 1.

Where is point 6? The part of the discussion regarding the calibration is very unclear and confusing and require thoughtful revising. The point number is written by mistake. The correct form is “point 2 on the blade 2” (numbering of the markers is presented in Figure 8). It is also corrected in the text.

I revised and also provided more explanation (to the paragraphs before Table 1) in this section.

P.11 line 14. Is the “blade elongation” physical? I.e. the blades become longer due to the centrifugal forces? Please explain what do you mean here.. This paragraph is added to page 10:

“The distance between the markers will barely change during the turbine operation due to the centrifugal forces and gravity, thus the change of the distance between the markers when the turbine is rotating can be used as another indication of the measurement inaccuracy.”

P.11 line 15. Where are the markers 1 and 2. If the marker numbers are important in the context, they should be shown in a figure. The numbering of the markers is shown in Figure 8. For more clarification, Figure 8 is referred in page 11, line 18.

P.12 line 1. The first paragraph: why this? Please provide more understandable explanation. I agree that more information is needed, therefore more detailed explanation about blade elongation is added to page 10 (paragraphs before Table 1).

P.12 line 13: "by looking at pictures"... What pictures? Please provide figures' numbers. The pictures that are taken and processed for the displacement measurement. This explanation is added to page 12 to avoid confusion.

Fig.12 needs numbering (e.g. a,b,c). The vertical axis of fig.12c, must be U_z . Is it depth? What is the coordinate system? How the values on the graphs correlate the elongation values? Absolutely true, the numbering is added to Figure 12 and the vertical axis of fig.12c is changed to U_z which represents the uncertainty in depth.

The coordinate system is shown in 5

Elongation values are introduced as an indication of the displacement measurements in this paper and are used to compare the accuracy of different calibration methods but uncertainty analysis quantifies the uncertainty of the measured displacement that is carried out with new proposed calibration method. Elongation value don't represent an specific coordinate but the uncertainty analysis using based on the law of error propagation represents the uncertainty values in x, y (in-plane) and z (out of plane) coordinates.

Interactive comment on “Establishing a robust testing approach for displacement measurement on a rotating horizontal axis wind turbine” by Nadia Najafi and Allan Vesth

Anonymous Referee #2

Received and published: 3 January 2018

Title: “Establishing a robust testing approach for displacement measurement on a rotating horizontal axis wind turbine” Paper No: wes-2017-49 Authors: Nadia Najafi, Allan Vesth

Dear Editors:

I would like to express that the current manuscript is suitable for publication. There are few minor corrections that must be addressed by the corresponding author:

Thank you for reconsidering the paper and constructive comments. In the following I tried to be precise in answering and satisfying the points.

** All the page numbers, reported in the answers, are based on the latest marked manuscript at the end of the document (after the responses to the reviewers).

1) I suggest, that the authors should mention the assumptions and/or limitations of the experimental setup. Could the experimental results be affected by using different materials with less or more flexibility or rigidity? It is a fair point. One of the assumptions is considering that the cameras follow the pinhole camera model that is added in page 4, second paragraph. The other limitation of the experiment is about camera synchronization that has been explained in page 14, second paragraph: “In the current study there is no external trigger or switch to start the cameras and they are triggered at the same time using software trigger (LabVIEW code) that could disturb the perfect synchronization between the cameras.” There are also other limitations in the setup regarding the turbine yaw and pitch that have been explained in paragraph 3 and 4 in page 14.

The proposed method for displacement measurement is not affected by the flexibility or rigidity but if the material is too flexible the normal distance between two markers would change due to the rotation and the change of this parameter during rotation cannot be used as an indication of measurement inaccuracy.

1) pp. 4, line 7: The selection of the distance of 7.5m between the camera and the turbine was a result of a dimensional analysis? How did you come up with this particular distance? According to the turbine dimensions the imaging area is chosen to be almost 2mx2m, the lens focal length is 40 mm and the camera sensor size is 11.26 mm x 11.26 mm. Based on these factors and pinhole camera model, the distance between the cameras and turbine is calculated to be 7.5 m.

2) In section 4, pp.7-8, I recommend add a flow chart of the tracking algorithm. Is it an open loop or closed loop algorithm? I added a flow chart at the end of the tracking algorithm section.

It is a closed loop.

3) In figure 12, reduce the scale for the y-axis as follows: U_x from 0.08-0.11, U_y from 0.08-0.11 and the mean value from 0.2 to 0.5. U_x exceeds a bit from 0.11 so I set the range for U_x and U_y to 0.08-0.11 and for U_z to 0.2-0.5.

4) I suggest that the conclusion should be focused on the most relevant results obtained in the experiments. Details about the experimental setup and procedure should be mentioned in the experimental setup section (pp. 3). Is it realistic to apply the proposed 3D technique to a 3.6 wind turbine? It is a fair point; I removed the part about the setup and procedure in the conclusion.

With considering some practical points the technique can be applied on a full size wind turbine. New information and explanation is provided in page 15 about applying the proposed technique in filed.

5) In pp. 14, line 16, the imaging area is supposed to be 2mx1.9m (see pp. 5, line 21). 2mx1.9m is the dimensions of the 2D calibration grid while the imaging area is a bit bigger (about 2mx2m) as it can be seen in Figure 4.

Regards, The reviewer

Interactive comment on “Establishing a robust testing approach for displacement measurement on a rotating horizontal axis wind turbine” by Nadia Najafi and Allan Vesth

Anonymous Referee #3

Received and published: 4 January 2018

General Comments

This work aims at developing a new 3D photogrammetric calibration technique which can be used for infield vibration tests on utility-scale horizontal axis wind turbines. For this purpose some dynamic experiments and measurements are conducted on a small scale wind turbine model in the lab.

Regarding the content, the methods described in the article can be very useful for the lab tests but unfortunately they are not applicable to the infield tests efficiently as claimed. Therefore, the paper needs significant major revisions in order to show that the proposed system can also be used in the field. Below you can see my recommendations

Thank you for reconsidering the paper and constructive comments. In the following I tried to be precise in answering and satisfying the points.

** All the page numbers, reported in the answers, are based on the latest marked manuscript at the end of the document (after the responses to the reviewers).

1- The term photometry is mis-used in the text. I think this word should be corrected as photogrammetry. Photometry: The science of measurement of visible light in terms of its perceived brightness to human vision. Photogrammetry: Determination of the 3D coordinates of the points on an object by using 2D images taken from different locations and orientations. **The comment is absolutely true. I replaced photometry with photogrammetry in the whole document.**

2- Photogrammetry can be easily used in small scale lab measurements performed in the controllable environments but infield tests have their own specific problems. For example, the authors mention about the accuracy of the device they used (Leica Nova MS50). The proposed accuracy is 0.035 mm in x and y directions and 1mm in z direction. However, this accuracy can never be reached in the field. It is not related to the accuracy of the device. In the field, the target will never be at standstill, it will be vibrating continuously. Even at low wind speeds the vibration amplitude can be +/- 10- 20 cm. Besides, due to the mean wind speed, this vibration will not be a zero average vibration. How can you claim that you will reach 1 mm accuracy if the target itself is vibrating +/- 10-20 cm. **I agree that the experiment in the field is much more challenging than the experiment in the lab and one of the challenges will be the vibrations during the calibration. Therefore the turbine vibrations should be considered during the calibration process and also**

uncertainty analysis. It could be suggested that the calibration is to be done in a calm weather condition with low wind to minimize the inaccuracies due to the wind induced vibrations. However the Leica Nova MS50 coordinate measurement is based on wave form digitizing technology (WFD) that is able to send out the short pulses with a frequency of up to 2 MHz toward the target [1] and it enables the Leica Nova MS50 to capture even very fast vibrations while the most dominant natural frequencies of the large wind turbines barely exceed 10 Hz.

To notify the challenges that need to be considered in the field measurement, more explanation has been added to page 15 that provides information in paragraphs 3 and 4.

[1] Maar, H., Zogg, H. M. (2014): WFD – Wave Form Digitizer Technology Leica Geosystems AG Heerbrugg, Switzerland

3- Leica Nova MS50 or similar total stations can only take measurement at one point at a time and then they move to the next data point. Therefore, it takes quite a lot of time to take measurements on 35 reference points. Could you please make an estimation related to time required to take measurements at 35 or maybe 100+ reference points? How can you guarantee that the wind speed so the vibration will not change within this period? Regarding the personal experience about Leica Nova MS50 coordinate measurement in the field, it takes less than 2 hours for the device to pick the coordinates of 100+ reference points.

The changes of vibration and wind speed should be considered during the calibration, as you noted. This issue could be addressed with synchronizing the image acquisition system and Leica surveillance device during camera calibration. This point is also mentioned in the added information about experiment in the field in page 14.

4- During the calibration at the site, how are you going to rotate the blades manually by a specific angle step by step? How are you going to move the device from one point to another and how are you going to guarantee that the physical conditions, blade pitch angle or yaw angle or wind speed (so the amplitude of the vibration) will be constant. These conditions can easily be fulfilled in a lab environment but not at the field. Under these circumstances bundle adjustment method is the only possibility because you take measurements at all the points simultaneously. The method you proposed may provide a higher accuracy in lab environment where calibration is performed in an isolated room where there is no wind but not in the field where there is always some sort of wind and noisy vibration. They are fair points and should be considered during full scale experiment. During the camera calibration in the field, we should break the turbine and then release the break shortly until it reaches the expected position. The pitch and yaw angles could also be locked within the calibration and the vibration amplitude and wind speed change can be addressed using the Leica surveillance device and camera synchronization.

5- The extrinsic calibration values are valid only for a certain yaw and pitch angle. During the rotation these values do change continuously, and then you will have to recalibrate the system by using the new values.

Are you planning to stop the turbine and to take some new calibration measurements with Leica system? You should explain in more detail how this method will be applied to the in-field tests? **The calibration method that is proposed in this paper is a 3D calibration due to the 3D distribution of the points on the rotor, nacelle and turbine tower. Therefore if the turbine yaws or the blades pitch within a reasonable range, the calibration is still valid for the measurement and there is no need for recalibration. However I absolutely agree that a comprehensive study should be done on the range where camera calibration is valid in the filed measurement.**

6- Illumination is always the most important problem. That is why the markers you propose can only be used for close range of photogrammetry. For long range measurements, using reflective markers is the only choiceto reach the sufficient contrast levels. In the text page 14 line 20 you wrote that matt markers should be used. This suggestion makes the situation even worse, for long range measurements the markers should be as bright as possible to increase the contrast, otherwise the markers cannot be seen from long distances. **Illumination and reflection are one of the main challenges in photogrammetry, as you mentioned. Using reflective markers is associated with some problems such as not enough contrast with the background during the day time, providing sufficient illumination for the markers on large structures, significant changes of reflection angles and reflection quality during turbine operation and also miscalculation of the rotational plan that cause systematic errors during the measurement. Non-reflective, black and white markers have been already used for displacement measurements on large structures such as bridges [1,2,3] that proves that optical long range measurements are possible using non-reflective markers and with choosing the proper size and shape for the markers. In addition they do not need extra light sources than the sun (day light) and with having matt markers even the day light reflection on the markers is avoided to a great extent that decreases a lot the systematic error due to the light reflection.**

- [1] Lee, J. J., and Shinozuka, M. (2006): Real-Time Displacement Measurement of a Flexible Bridge Using Digital Image Processing Techniques, pp.105-114, Experimental Mechanics (46).
- [2] Feng, D., Feng, M. Q., Ozer, E., and Fukuda, Y. (2015): A Vision-Based Sensor for Noncontact Structural Displacement Measurement, pp.16557-16575, Sensors (15).
- [3] Yang, J., Peng, C., Xiao, J., Zeng, J., and Yuan, Y. (2012): Application of videometric technique to deformation measurement for large-scale composite wind turbine blade, pp.292-300, Applied Energy (98).

7- Page 2 line 5 “the transducers load the structure with their weight that changes the dynamic properties of the structure and need expensive correction”. This statement is correct only if you perform some tests on very small models. I agree that an accelerometer of 100 grams can be considered as an added mass for a small scale model but weight of a real wind turbine or a real bridge is not affected by the weight of an accelerometer of 100 grams. Could you please remove this sentence? **The sentence is removed.**

8- P2 line 23 “is” should be “are”. **Fair point, it is corrected.**

9- P8 line 5 please change “angel to “angle”. **Fair point, it is corrected.**

10- Page 11 line 13: You wrote that rotational speed of 30 rpm can cause an elongation on metal rod blades. Could you please check these values again? I am not sure but I do not think that such a low speed can cause a noticeable elongation on metal rods? **That is true, this part is removed from the text.**

11- Page 16: It is not clear how to read and interpret Table 1. Could you please explain in more detail what the distance between the light rays is? A sketch would be very helpful. **More explanation regarding Table 1 is added to page 11, just before Table 1.**

Establishing a robust testing approach for displacement measurement on a rotating horizontal axis wind turbine

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Abstract. Health monitoring by conventional sensors like accelerometers or strain gauges becomes challenging for large rotating structures due to the feasibility, sensing and data transmission. In addition acceleration measurements have low capability in presenting very small frequencies which happen so often for large structures (For instance frequencies between 0.2 and 0.5 Hz in horizontal axis wind turbines). By contrast the displacement measurement using stereo vision is rapid, non-contacting and also distributed over the structure. The sensors are cheaper and easier to be applied in many places on the object to be measured. Horizontal axis wind turbines are one of the important large rotating structures which need to be measured and monitored in time to prevent damage and failure and the blade tip position is one of the key parameters to measure to prevent blade hitting the turbine tower.

This paper presents a **clearly described and easily applicable well-defined** procedure for measuring the displacement on the components of a rotating horizontal axis wind turbine (HAWT) with ~~stereo photometry~~ **stereophotogrammetry**. Paper markers have been applied on the rotor and tower of a scaled down HAWT model in the workshop and the displacement measurement method has been demonstrated by measuring displacement during operation. The method is mainly developed in two parts: 1) the camera calibration and 2) tracking algorithm. We introduce an efficient camera calibration method for measurement in the large field of views that ~~has~~ always has been a challenge. This method is easy and practical and offers better accuracy compared with 2D traditional camera calibration. The tracking algorithm also worked quite successfully and kept tracking the points during rotation within the measurement time. Finally the accuracy analysis has been conducted and has shown the better accuracy of the new calibration method compared with 2D traditional camera calibration.

1 Introduction

Regarding the increasing industrial advances and the world's population growth, the fossil fuel sources will soon not meet the human need for energy. In such a situation wind energy is an environmentally friendly alternative that can decrease the dependency on the declining fossil fuels (Herbert et al., 2007). Prospering the wind turbine technology has led to important concerns about the reliability of the energy production and wind turbine efficiency and reliable turbine operation also requires proper experimental tools and high quality testing methods to monitor the turbine behaviour.

Traditional contact transducers such as strain gauges and accelerometers have been used for vibration analysis, health monitoring, Damage detection and structural displacement of wind turbines (Weijtjens Larsen et al., 20022017; Yang et al., 2014; Osgood et al., 2010 Lorenzo et al., 2016 and Manzato Herlufsen et al., 20022014) and other large structures like bridges (Hoffmann, 1989; Fukuda et al., 2013; ~~and~~ Park et al., 2005; Ye et al., 2012; Xia et al., 2014 and Siriwardane, 2015.) but they have difficulties in measuring in large scale; the installation process that often includes wiring is costly and time consuming, ~~and the transducers load the structure with their weight that changes the dynamic properties of the structure and need expensive correction (Ashory, 1999).~~ The measured signal from conventional sensors such as accelerometers is not very accurate in measuring low frequencies of the structure to be studied (For instance frequencies between 0.2 and 0.5 Hz in horizontal axis wind turbines) and is including the centrifugal components (Najafi and Paulsen, 2017). In addition the contact transducers can only measure the structure in a few numbers of points and increasing the measurement points creates additional cost and complication (Hunt, 1998). As an alternative, non-contact optical measurement techniques provide faster and cheaper possibility to measure displacement on large and rotating structures such as wind turbines. ~~Stereo photometry~~Stereophotogrammetry is one of the common optical techniques for motion tracking of the objects that enables 3-D displacements measurements. ~~Stereo photometry~~Stereophotogrammetry or stereo vision estimates the 3D coordinate of the points using two or more 2D images taken from different angles. The preparation time is short and it could measure at many points on large structures.

The displacement of the turbine components (blades and tower) is an important parameter in analysing the rotor performance and structural behaviour of the turbine during operation. ~~Stereo photometry~~Stereophotogrammetry has been previously employed to estimate the strain and full displacement field of the turbine blades with digital image correlation (DIC) for investigation of the relative out of plane blade deflections (Winstroth, et al., 2014), rotor vibration measurement (Warren, et al., 2010a and Poozesh, et al., 2016) and blades damage detection (Leblanc, et al., 2013 and Zarouchas and Hemelrijck, 2014). DIC gives the continuous displacement distribution and is computationally expensive in monitoring large scale structures but 3D point tracking (3DPT) which measures displacement in discrete points, is the preferable approach for outdoor and large scale experiments. In 3DPT, the optical targets, that can be simple paper markers (reflective or not reflective), are mounted at different places of the structure, as many as desired, and their 3D coordinates ~~is~~are tracked in time. 3DPT has been used for displacement measurements of the turbines in the recent years. The displacement measurement via 3DPT has been used to predict the full field dynamic strain of a model scale wind turbine blade (Baqersad, et al., 2015). However, stereo vision is new in measuring vibration; it showed good agreement with conventional transducers like accelerometers and strain gauges in this filed (Warren, et al., 2010b and Najafi, et al., 2015). In, Najafi and Paulsen, 2017, 3DPT has been used to study structural vibrations of a model scale vertical axis wind turbine. Najafi and Paulsen, 2017, have investigated the challenges of using stereo vision for vibration analysis of complex geometries with sharp curvatures and out of plane components. In (Prowell, et al., 2011; Prowell, et al., 2012 and Paulsen, et al., 2012) the displacement measurements by point tracking ~~stereo photometry~~stereophotogrammetry is used for structural response and modal properties of utility-scale horizontal axis wind turbines.

The ~~current~~ study is focused on establishing a ~~well-defined~~ clearly described and easily applicable procedure to measure displacement on the components of a rotating horizontal axis wind turbine using stereo vision technique. A scaled down HAWT model, is used to demonstrate the displacement measurement method. Camera calibration is one of the main challenges in measurement in large field of views. ~~Camera calibration that~~ links the 3D coordinate of the points in the world to their corresponding 2D coordinate in the image plane.

Traditional way of calibration uses a calibration object with known and precise coordinates to calibrate the camera. This method is accurate and also efficient but it is unpractical for large field of view applications because of the calibration object size. There are also other techniques of calibration with no need to calibration object, they are called self-calibration. Self-calibration uses epipolar geometry of stereo pairs to reconstruct the 3D coordinates. These methods are flexible but the final results are not always precise and reliable because there are many parameters that need to be estimated (Medioni and Kang, 2005). In this study we updated the traditional calibration method for large field of views to be easier, faster and more practical. We also compared the results of the updated 3D calibration method with the traditional calibration that is conducted with a large grid in the background and the comparison shows the better accuracy of the new 3D calibration procedure.

15 2 Experimental setup

The case study is a scaled down model of 3.6 MW ~~Envision~~ turbine (see ~~Figure 1~~Figure 1). The rotor diameter is 1640 mm and the blades are made from Aluminium with rectangular cross section of 5mm×8mm. The tower is also an Aluminium rod with the height of 1600mm and the cross section of 16mm in diameter. The rotational speed of rotor is between 0-150 rpm. A wire is twisted around the individual blades to prevent vibrations induced by vortex that has formed behind the rectangular shape of the blade.



Figure 1: scaled down model turbine

Stereo vision measurement system contains two Basler acA2040-180km cameras equipped with 40 mm (focal length) Nikon lenses. The maximum frame rate of the cameras is 187 frames per second (*fps*) for full resolution-size images. The image acquisition system has limited capacity; therefore the longest acquisition time of stereo system with maximum frame rate (187 fps) is about 16 seconds. However with decreasing the frame rate the acquisition time increases, for instance the motion of the turbine can be tracked for about 150 seconds with 20 fps. Nevertheless with upgrading the acquisition system the measurement time can be modified.

In this experiment the cameras are placed about 7.5 meters away from the turbine while they are apart by about 3.5 meter.

According to the turbine dimensions the imaging area is chosen to be about 2m×2m. Based on the focal length, camera sensor size and assuming that the cameras follow the pinhole camera model, the distance between the cameras and turbine is calculated to be 7.5 m.

This setup satisfies the rule of thumb which says the distance between the cameras should be between at least 1/3 and 1/3 time of the distance between the cameras and the test object; it can be up to 3 times of the distance as long as all the targets on the object can be seen in the stereo image pairs, and object.

Comment [alve1]: Is red when I print it

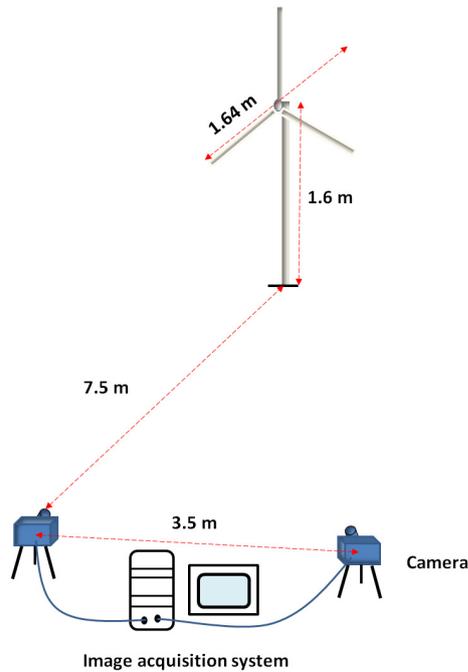


Image acquisition system
Figure 2: Stereo vision system set up

5 The simplest marker used in stereo vision is circular shape with a good contrast with the background and the center of the marker is considered to be tracked. According to (Ozbek and Rixen, 2013) curvatures of the structure where the markers ~~is~~ are applied, lead to perspective errors that needs to be corrected. In other words, in horizontal axis wind turbines, some parts of the blades are curved or deformed due to the loading during the rotation, this deformation and also the relative angles between camera and turbine causes the changes in the shapes of the marker in the image from circle to the ellipse. Thereore ~~and the real center of the circular marker should be calculated by knowing the exact relative angles and blade deformation at the marker position that the corresponding error correction~~ is quite challenging due to the unknown instant blade deformation. To avoid these difficulties, we have changed the marker shape to the following shape, shown in Figure 3 ~~Figure 3~~, with the diameter of 4 cm. In this case there is no need to calculate the center of the marker and it can be found using robust corner detection image processing algorithms independent from the marker shape in the image and blade curvatures. ∴

10

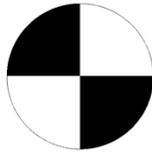


Figure 3: Marker shape

3 Camera Calibration

Camera calibration is the estimation of intrinsic and extrinsic parameters of the cameras to relate the 3D coordinates of the word to 2D coordinate of the image. Extrinsic parameters define the location and orientation of the camera that contain the translation vector and rotation matrix. Intrinsic parameters describe the optical, geometrical and digital characteristics of the camera such as focal length, image centre in pixel coordinates, the effective pixel size in the horizontal and vertical directions, and the radial distortion coefficient. Traditional camera calibration is the most common way of calibrating cameras and has been studied and improved during years by different researchers (Tsai, 1987; Weng, et al., 1992 and Zhang, 2000). This method uses a calibration object including a number of points with known coordinate to estimate the camera parameters. The traditional calibration is divided to 3 methods based on the calibration object dimensions: 3D, 2D (planar) and 1D (linear) calibration (Medioni and Kang, 2005). 3D calibration can be conducted very efficiently with very high precision but it requires expensive equipment and elaborate setup in the traditional calibration procedure (Faugeras, 1993), but however 2D traditional calibration is easier and less expensive (Sun and Cooperstock, 2005).

In this section two calibration methods are applied: at first the cameras are calibrated using a 2D calibration board with known coordinates and in the second part a new 3D calibration approach is introduced.

3.1 2D traditional camera calibration

The 2D traditional calibration has been conducted with a 2D printed grid applied on a wooden board. The dimensions of the grid are $2m \times 1.9m$ and it contains 21 horizontal and 20 vertical lines that intersect at 420 points with known coordinates that are 10 cm apart in horizontal or vertical direction.

The exact positions of the grid point in each image are determined using image processing algorithms: Firstly a part of the grid that is common between the field of view of both cameras is chosen, and then 8 point on the borders of that area is picked (see Figure 4 Figure 4: Left). A fraction of the image around each of the border point is taken (image window) and the exact position of the points is given by intensity median of the image window.

The coordinates of windows around all the grid point are estimated using interpolation between the border points and finally the exact positions of the grid points in each image are determined as the intensity median of the windows (Figure 4 Figure 4: Right).

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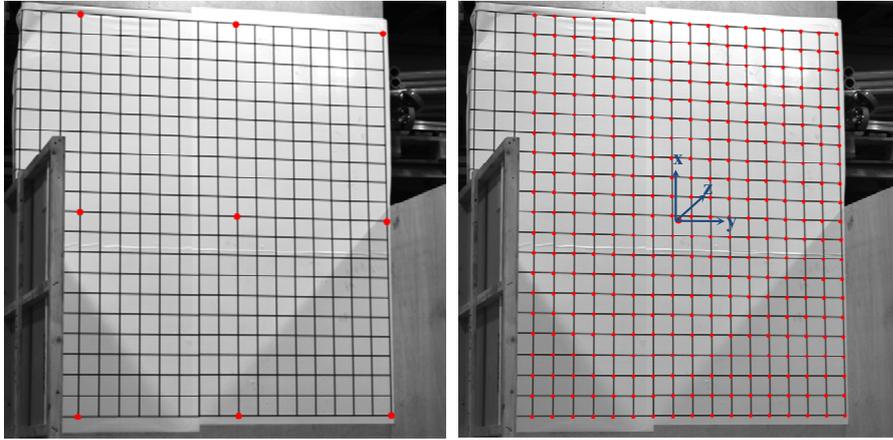


Figure 4: **Left:** 8 points on the borders of the common between the field of view of both cameras on the calibration grid, **Right:** Identifying the calibration points in calibration grid

After getting the exact pixel positions of the grid points in the image and also having the coordinates of the points in the real world the traditional calibration builds the equations that relate the coordinates of the world to the coordinates of the images taken by the camera. And finally intrinsic parameters of the camera (focal length, chip size, image center, ...) and extrinsic parameter (translation and rotation matrix) are defined.

3.2 3D updated camera calibration with [a surveillance device with a laser range finder](#) ~~Leica~~

Traditional 3D calibration method can be conducted very accurately, as it has been referred at the beginning of this section, but it needs expensive and elaborate setup and expensive equipment such as two or three orthogonal planes. Setting up the traditional 3D calibration in large field of views, like full scale wind turbine experiment, is not feasible due to the difficulties in providing a precise calibration object. In our new calibration method, instead of using a huge 3D calibration object, we used the markers that are applied on the turbine for the sake of measurement, as the calibration points. A Leica surveillance ~~device~~ (Leica Nova MS50) ~~is our smart device to~~ determine the exact position of the points quite accurately and then the coordinates are used for 3D calibration of each camera. [Leica Nova MS50, is a surveillance device with a laser range finder that uses advanced technologies for 3D laser scanning, imaging and GNSS \(Global Navigation Satellite System\) positioning.](#) The ~~Leica~~ accuracy in x and y directions is dependent on the distance between the Leica [Nova MS50](#) and the object, hence the accuracy in x and y directions in the current case is about $0.0349mm$. In addition the Leica [Nova MS50](#) accuracy in depth (z direction) is $1mm$ for measuring on reflective surfaces.

During the calibration the rotor was rotated (manually) by a specific angle step by step, in order to cover the whole rotor area by the calibration points and establish the collection of known coordinates for camera calibration.

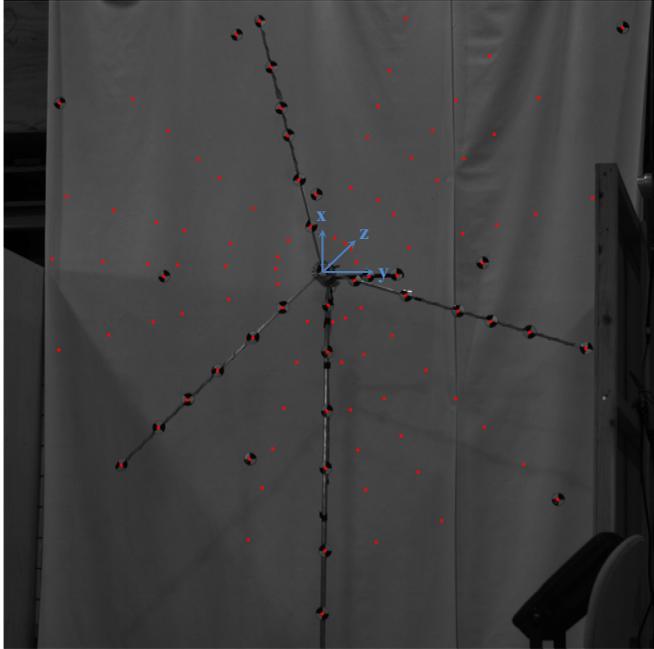


Figure 5: calibration points in the new method. The blue axes show the world coordinate system

4. Tracking algorithm

5 To measure the displacement of the markers during the rotation, a tracking algorithm has been developed. The main steps of the algorithm are:

- 1- Picking the coordinates of the markers in a number of image sequences during a cycle of rotation with equal intervals between the sequences. For example if the camera takes 40 pictures during one rotor revolution~~the rotor rotates one cycle within 40 pictures~~, we picked the coordinate of the markers in every 4 pictures to estimate the path of each marker. In this step an ellipse equation is fitted to the markers path during one rotation.

10

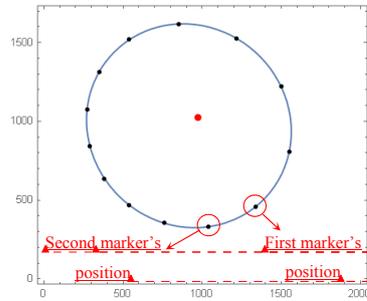


Figure 6: Elliptical path of a marker in the image coordinates during rotation, **Black dots:** the coordinate of the marker that has been picked with equal intervals, it means there is-are $N1$ coordinates of the marker between every two black dots, **Blue line:** the fitted ellipse, **Red dot:** the center of the ellipse

- 2- **Initial guess for angular deflection between image sequences:** The angle between the lines that connect the ellipse center to the first and second picked marker coordinates on the ellipse in step 1-4 (black dots in Figure 6) is calculated and by knowing the number of image sequences between the first and second position of the marker point ($N1$) on the ellipse, the first guess for the angular deflection between image sequences is obtained. As the turbine rotational speed is not fully constant during rotation, we need to update the angular deflection in each sequence.

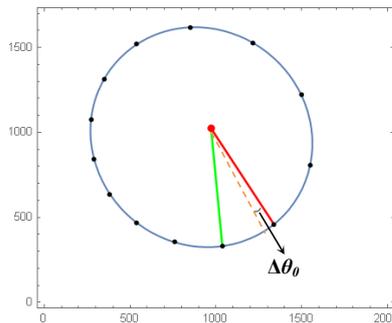


Figure 7: **Red:** The line between the elliptical path center and the first position of the marker at time $t=t_0$, **Green:** the line between the center of the elliptical path and the position of the marker after a number of sequences

- 3- With the initial estimation of the angular deflection between the image sequences ($\Delta\theta_0$) and also the elliptical path of each marker, the approximate position of the marker in the next sequence (time of $t_0+\Delta t$) is estimated.
- 4- An image window is established around the approximate position of the marker and the exact position of the marker is calculated using the Harris-Stephens corner detection algorithm in the window. This algorithm is described in Harris and Stephens, 1988.
- 5- By knowing the exact position of the marker, the exact angular deflection is calculated ($\Delta\theta$).
- 6- The approximate marker position in the next sequence is estimated using the angular deflection in the previous sequence. On the other hands the initial guess for the angular deflection in each time step is the angular deflection of the previous sequence ($\Delta\theta_0 = \Delta\theta$).

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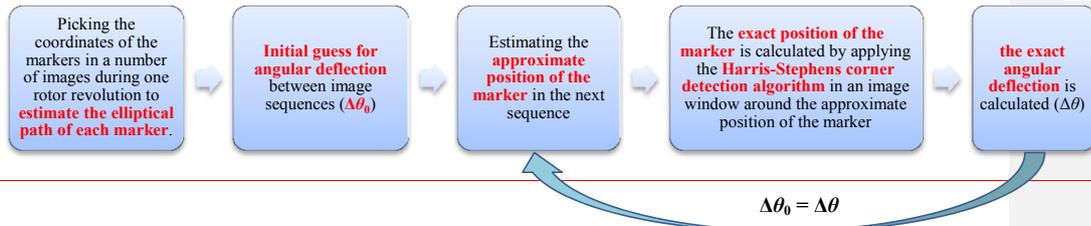
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7- The exact position of the marker is estimated by repeating the algorithm from step 3-3 to 5-5. The flowchart in [Figure 8](#) explains briefly the tracking algorithm.



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Figure 8: Tracking algorithm flowchart

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5. Results and discussion

After calibrating the cameras by traditional and updated calibration methods, the 2D positions of the markers in the image are found during the rotation using the tracking algorithm. The markers that are followed in time are shown in [Figure 9](#).

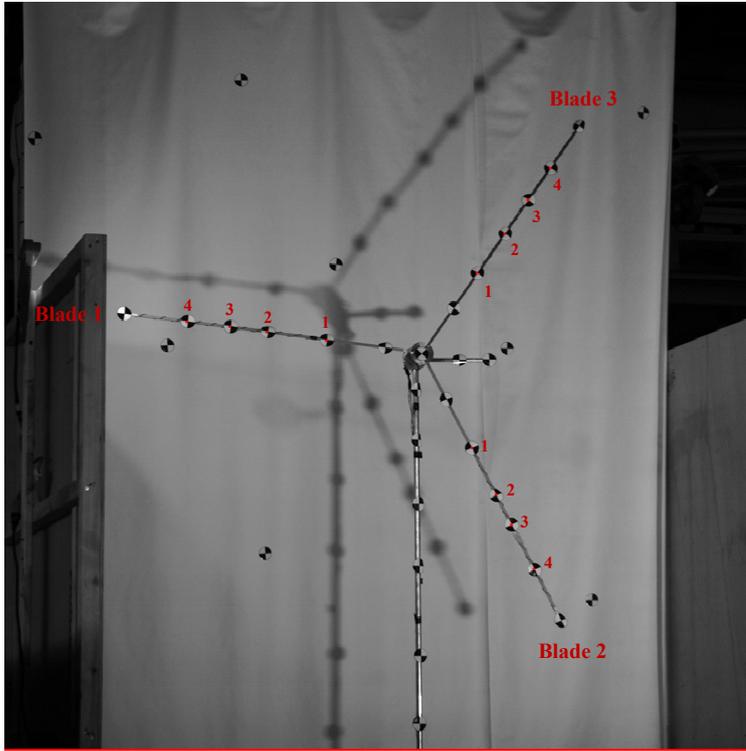


Figure 9: Marker numbering on the rotor

The line of sight from each marker to each of the cameras is calculated by both calibration methods and the intersection of two lines of sights is found as the 3D position of the marker (stereo triangulation). The 3D updated calibration has been done with different numbers of calibration points to compare the results: 1) all the 111 points including the points on the turbine rotor, tower and on the background, 2) 103 points including the points on the turbine rotor and tower, 3) 35 points of the points on the turbine rotor and tower.

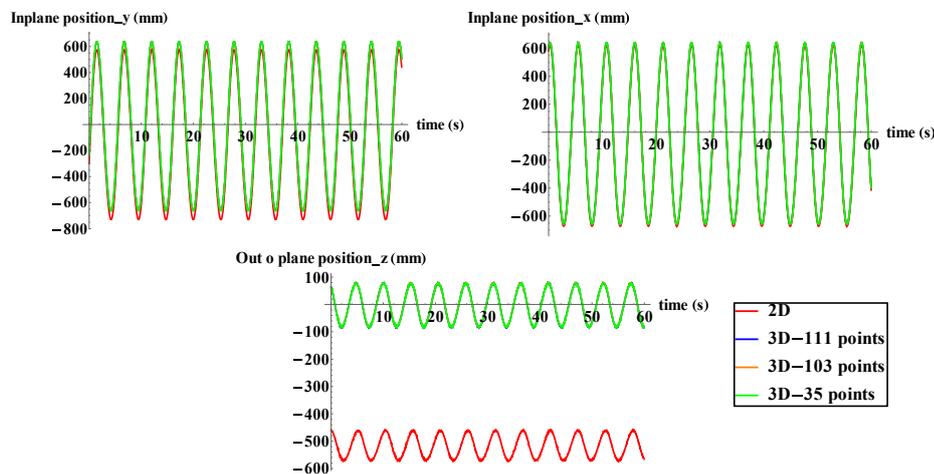


Figure 10: Displacement time series for point number 4 with different calibrations (plots corresponding to 3D calibration are almost on top of each other)

5 | It can be seen in Figure 10 that there is an offset, especially in depth direction, between the displacement obtained by the traditional and updated calibration methods; this offset is due to having different origin of the coordinate systems in two different 2D and 3D calibrations. There are also other minor differences between traditional 2D and new 3D calibrations (is more obvious in in-plane positions) that a part of it can be due to the slightly different direction of the coordinate axes.

10 | For comparing calibration methods two different indicators are investigated: 1- the distance between the light rays/lines of sight at the intersection position 2- the distance between two markers during rotation.

The lines of sight/light rays from the marker to the cameras do not exactly intersect in the space due to the inaccuracies and the 3D position is regarded as the point with minimum distance from two rays-lines of sight (Trucco and Verri, 1998). Therefore the distance between the lines of sight is considered as an indication of measurement inaccuracy that is mainly caused by calibration uncertainties, light reflections and also by other environmental and physical factors.

15 | The distance between the markers will barely change during the turbine operation due to the centrifugal forces and gravity, thus the change of the distance between the markers when the turbine is rotating can be used as another indication of the measurement inaccuracy.

20 | In the following table the averaged and maximum value of the distance between the lines of sight/light rays turbine during rotation for point number 6-2 on blade 2 are listed for different calibrations and in different rotational speeds. The light and other environmental factors are almost the same in all the measurements, therefore the different values of lines of sight distances are mostly due to different calibrations. The photography sampling frequency is 50 frames per seconds and the recording time is 1 minute.

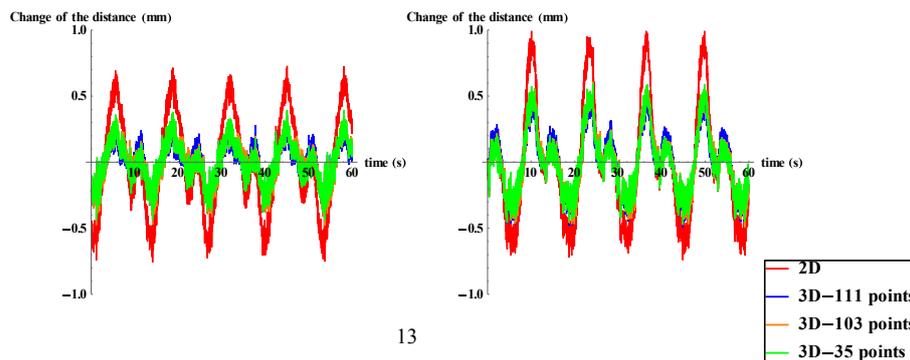
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Table 1: The distance between the lines of sight light-rays during rotation for point number 62 on blade 2 and for different calibrations

	5 Hz		10 Hz		30 Hz	
	Mean	Max	Mean	Max	Mean	Max
2D- calibration grid	34.63 mm	79.71 mm	35.24 mm	77.75 mm	43.99 mm	82.81 mm
3D- 111 points	2.81 mm	12.09 mm	2.66 mm	10.69 mm	5.44 mm	9.63 mm
3D- 103 points	2.79 mm	11.44 mm	2.60 mm	10.09 mm	5.05 mm	9.13 mm
3D- 35 points	3.04 mm	13.45 mm	3.08 mm	11.84 mm	5.35 mm	10.42 mm

It is obvious in Table 1 that the distance between the rays-lines of sight is much larger in the measurement with traditional 2D calibration using the grid compared to the measurement with the new 3D calibration using Leica. This comparison proves that the new calibration with Leica Nova MS50 is more accurate than the traditional 2D calibration, even with much fewer calibration points. The distances between the light-rays lines of sight in measurements with different numbers of the 3D points are relatively close but the measurement of the 3D calibration with 103 points on the turbine, shows slightly better result. It can be seen in Table 1 that by adding the background calibration points the distance between the rays-lines of sight does not change significantly. This is a good and practically relevant point for full scale turbine measurement that shows having other calibration points than the points on the turbine is not necessary and does not improve the displacement measurement quality. It is expected to see better results with more calibration points; however 3D calibration with one third of the turbine calibration points still looks still-acceptable. This effect of the number of the calibration points on the calibration quality is an important parameter that also needs to be checked in the full scale experiment.

According to (Ozbek and Rixen, 2013), distance between the target points for a real turbine remains constant during rotation. In the present study, the blades of the model turbine are pretty flexible; hence the normal distance between the markers might change a little at higher rotational speeds such as 30 rpm especially at the blade tip region. Therefore the blade elongation is studied for rotational speed of 5 rpm as an indicator for calibration precision. In Figure 11 the change of the distance between markers 1 and 2 on blade 1 (shown in Figure 9) that are about 146 mm apart and markers 1 and 2 on blade 3 that are about 145 mm apart are plotted for the different calibrations approaches:



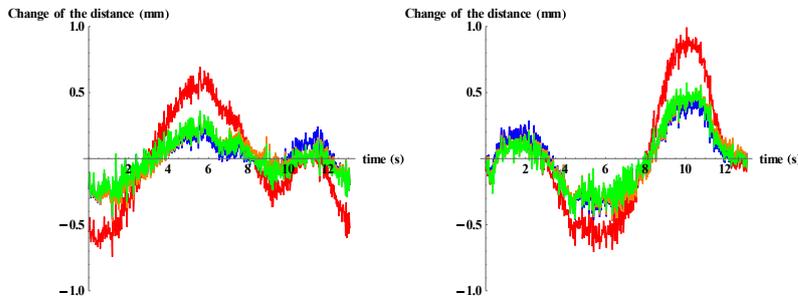


Figure 11: Elongation between markers 1 & 2 on blade 1(left) and blade 3 (right) in one minute (above) and during one cycle of rotation (bottom) with different calibrations

The larger changes of distance between the markers with the 2D calibration could notify the less accuracy in this calibration compared to the 3D calibrations with Leica [surveillance device](#).

The distance between two markers changes periodically in [Figure 11](#)[Figure 11](#)[Figure 10](#), no matter which calibration method is used to obtain the displacement. The distance between the other two markers at almost the same area of the blade (markers 1 and 2) are also checked for the sake of reliability and repeatability and they also revealed the periodic behaviour of the elongation between markers that is due to the repeating errors during operation. To investigate this behaviour, the

spectrum of the distance measured with 3D calibration has been plotted in [Figure 12](#)[Figure 12](#)[Figure 11](#):

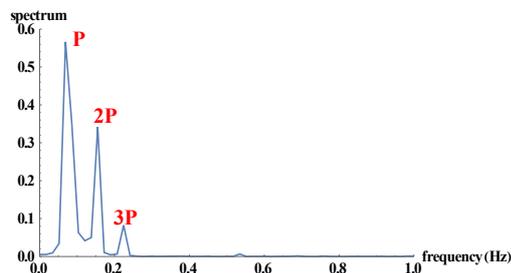


Figure 12: Power spectrum of the distance changes between points 1 & 2 on blade 3 calculated by 3D calibration using turbine points

[Figure 12](#)[Figure 12](#)[Figure 11](#) shows that the periodic behaviour of the elongation between markers is dominant by 1P and 2 P, where P is the rotor rotational frequency (5 rpm \approx 0.083 Hz). This could be because of the physical problems such as the light reflection, calibration inaccuracies, geometry miscalculations and also camera un-synchronization.

By looking at the [pictures/images that are taken and processed for the displacement measurements](#), it can be seen that each marker in [Figure 11](#)[Figure 11](#)[Figure 10](#) is exposed to strong reflection once during one cycle that will be two times for a pair of markers, this could explain the 2P peak in the spectrum. For decreasing the unwanted reflections during displacement measurement, the markers can be printed with matt coating.

The geometry miscalculation which is mainly happening for circular markers is less likely happening in the current study. On the other hands the image of circular markers changes to ellipse ~~in the image~~ due to the blade loading and deformation during rotation and relative angle between camera and turbine. To calculate the center of the circular marker from its elliptical image, the knowledge about the exact angle of the rotor plane is required but in the current case no center calculation is needed due to the specific shape of that marker (Figure 3Figure 3Figure-3).

In the current study there is no external trigger or switch to start the cameras and they are triggered at the same time using software trigger (LabVIEW code) that could disturb the perfect synchronization between the cameras. This also could be one of the sources that makes the P peak occurred in the spectrum. The effect of the camera un-synchronization would be obviously more pronounced in full scale experiments with very larger dimensions and higher rotational speeds; therefore the image acquisition system should be equipped with the external trigger during full scale turbine testing.

There are also other challenges that should be considered during the full scale operational turbine displacement measurement via the technique that is developed in this study. One of the main challenges is turbine vibrations due to the wind within the camera calibration that will not happen in the workshop. It could be suggested that the calibration is to be done in a calm weather condition to minimize the inaccuracies of the coordinate measurement by Leica surveillance device due to the wind induced vibrations of the targets. Furthermore the wind induced vibrations should be considered in uncertainty analysis, however the Leica Nova MS50 coordinate measurement is based on wave form digitizing technology (WFD) that is able to send out the short pulses with a frequency of up to 2 MHz toward the target [Maar and Zogg] and it enables the Leica Nova MS50 to capture even very fast vibrations while the most dominant natural frequencies of the large wind turbines barely exceed 10 Hz. In addition the camera and Leica surveillance device should be synchronized during the calibration process to capture the changes of the turbine vibrations.

Another complexity about the field measurements is the changes of the wind speed and direction that lead to changes in turbine yaw and blade pitch angles. The calibration method that is proposed in this paper is a 3D calibration due to the 3D distribution of the points on the rotor, nacelle and turbine tower. Therefore if the turbine yaws or the blades pitch within a reasonable range, the calibration is expected to be still valid for the measurement. However a comprehensive study should be done on the yaw and pitch angles range where camera calibration is valid in the field measurement.

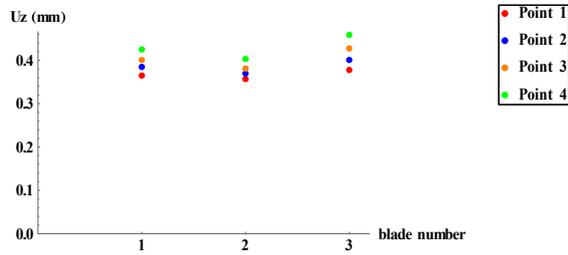
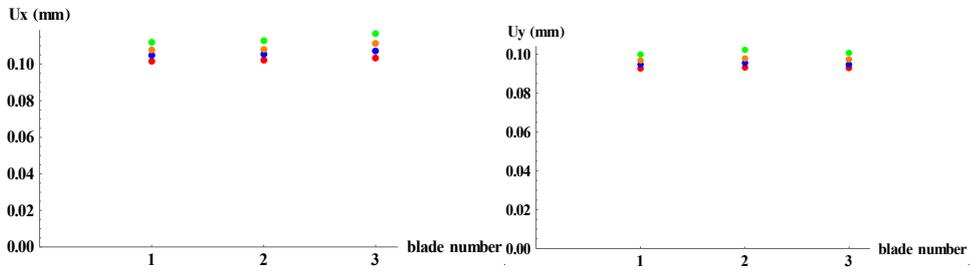
The uncertainty of the measured displacement signal obtained with 103 point calibration is calculated using the generalized method based on the law of error propagation in a linear camera model of a stereo vision system. In this method, which is very well described in (Chen, et al., 2008), the uncertainty propagation in stereo reconstruction is explained in two main stages: camera calibrations and 3D triangulation to obtain the 3D coordinates from 2D projections in the images. In ~~Figure 13Figure 13Figure 12~~ the mean value of the position determination uncertainty in x (U_x), y (U_y) and z (U_z) directions is presented for markers shown in ~~Figure 9Figure 9Figure 8~~:

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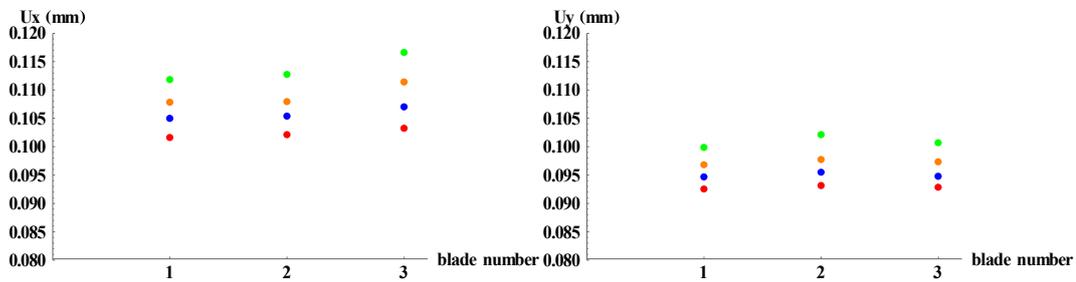
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(a) (b)



(c)

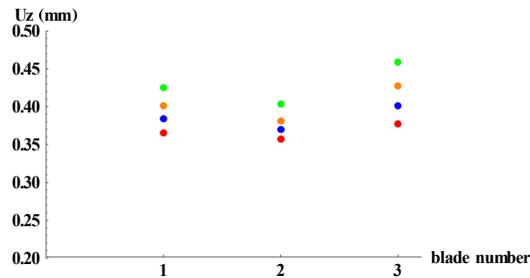


Figure 13: Mean value of the uncertainty for rotor points

It can be seen in ~~Figure 13~~ ~~Figure 13~~ ~~Figure 12~~ that the uncertainty values do not change significantly from root to the tip of the blade that show that the lens distortion is really negligible.

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6. Conclusion

In this paper, a ~~clearly described and easily applicable stereophotogrammetry~~ ~~well-defined stereo photometry~~ approach is introduced to measure the displacement of a rotating horizontal axis wind turbine. Camera calibration and marker tracking algorithm are two topics that are studied in this work.

Camera calibration for large field of views normally involves a lot of challenges. The traditional way of calibration that uses a calibration grid with known points is impractical for large scale uses, with a modern size wind turbine the calibration grid would at least need to be 120x120 meters, and other calibration techniques such as self-calibration are not always precise and reliable.

In this study a new 3D calibration method has been developed; ~~the method that~~ is especially suitable for large field of views; ~~in this study the current case~~ an operating horizontal axis wind turbines. The new 3D calibration method is easier, faster and has the big advantage ~~of that it~~ ~~avoiding~~ the use of a calibration grid. Instead of the calibration grid the measurement points themselves are used as the calibration points by determining their coordinates. A Leica surveillance device with a laser range finder is used in the calibration process to determine the exact position (x,y,z) of the calibration points ~~while the turbine is at standstill. During the calibration the rotor is rotated with a specific angle step by step, to cover the rotor plane of the turbine and establish the collection of known calibration points. The coordinates extracted by Leica are then used for a 3D calibration of each camera using a defined procedure.~~ The markers are then used as 3D sensors of ~~stereo photometry~~ ~~stereophotogrammetry~~ after the calibration and the cameras record their motion to ~~archive~~ the displacements by post processing of the images.

A comparison between the results from the new 3D calibration method and the traditional 2D calibration that is using the calibration grid shows a higher accuracy ~~using for~~ the new 3D calibration procedure.

The new 3D calibration procedure was then conducted using different numbers of the calibration points on the turbine components and also on the background. It is concluded that the background points are not necessary and ~~didn't do not~~ improve the calibration quality. ~~This~~ is very important in the full scale experiment as it would be problematic to install background points on a modern size wind turbine. The investigations also showed that decreasing the calibration points ~~until~~ ~~down to~~ 35 points on the turbine for the imaging area of $2m \times 2m$, still gives acceptable quality on the 3D calibration. To measure the displacement of the markers during the rotation, a tracking algorithm has been developed based on the circular motion of the rotor markers and the robust corner detection image processing algorithms for determination of the marker's position. This algorithm that keeps tracking the markers robustly during operation, updates its parameters based on the angular deflection of the marker in the last time step and the elliptical path of the markers in the images during the rotation.

Light reflection and camera un-synchronization are discussed as the main sources of the error during measurement that can be addressed using matt markers and also external trigger for the cameras in full scale experiments.

Acknowledgments

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