Field-test results using a nacelle-mounted lidar for improving wind turbine power capture by reducing yaw misalignment

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Abstract. In this paper, a nacelle-mounted lidar was used to improve the yaw alignment of an experimental wind turbine. Using lidar-recorded data during normal operation, an error correction value for the nacelle vane wind direction measurement used in the yaw controller was determined. A field test was then conducted in which the turbine was operated with and without the correction applied to the yaw controller. Results demonstrated a significant increase in power capture. In addition, the study includes analysis on the impacts on loading of applying this yaw correction. The study demonstrates a successful application in field testing of using a nacelle-mounted lidar to improve turbine performance.

1. Introduction
Most modern utility-scale wind turbines actively control their yaw angle to maintain alignment with the wind. A typical yaw control system uses a wind vane mounted towards the rear of the nacelle as the feedback sensor. The controller is often of a slow, “on-off,” nature, with discrete yaw motions occurring only periodically to avoid overworking the yaw system.

Recently, there has been growing interest in how this control could be improved. Improving the alignment of the nacelle should lead to increased power capture. This can be seen by considering the following formulas concerning wind speed, direction, and power (from [1]):

\[ P_{\text{max}} = \frac{1}{2} \rho A_r V_p^3 C_p \]  
\[ V_p = V_0 \cos(\theta_E) \]

Equation 1 provides the power that could be captured by a wind speed $V_p$, perpendicular to the rotor plane, given air density $\rho$, rotor area $A_r$, and wind turbine power coefficient $C_p$. In Equation 2, this perpendicular component of wind speed is related to the free-stream wind speed $V_0$ and the cosine of the yaw alignment error $\theta_E$. This equation implies that the power extracted from the wind is reduced by the cosine of the yaw error cubed. However, experimental results have shown that this relationship could in fact be cosine-squared [2], or even cosine [3],...
depending on the aero-elastic properties of the turbine. The amount of power loss for a certain yaw misalignment is turbine-dependent.

There are several sources that can produce a yaw error in turbine control. The first is the wind direction; it typically changes more frequently than the yaw controller can respond to and make corrections. Theoretically, it may be possible to reduce yaw misalignment by yawing more frequently. However, this is an impractical solution as it implies significantly more wear on the yaw system [4].

A second source of yaw error could be caused by inaccuracies in measuring the true wind direction with a nacelle-mounted wind vane. Correcting these inaccuracies represents a more plausible path to improving yaw control as it does not imply greater amounts of yaw actions but could still improve power capture. This correction could be implemented either by detecting an error or bias in the wind vane measurement, or replacing the wind vane with a more accurate sensor.

In [1, 5], an empirical study was conducted that compared the wind direction measurement of a nacelle vane on the three-bladed Controls Advanced Research Turbine (CART3) located at the National Wind Technology Center (NWTC), with a nearby and normally upwind meteorological (met) mast. The study showed that the nacelle vane became more biased as the rotor speed increased. A rotor-speed-dependent correction function was derived and used to un-bias the yaw controller. Running the turbine with this correction function applied yielded a significant improvement in power capture. The conclusion of the study noted that although the final controller used only existing sensing equipment (the nacelle vane), the derivation of the correction function relied on upstream met tower wind measurements that are often not available. A nacelle-mounted lidar could provide a more practical way to learn this correction, as suggested in [1] and [6], as many turbines do not have a dedicated met mast. A lidar, which can be moved from turbine to turbine, is more feasible (in many cases) than installing a met mast. Also, as [6] points out, attempting to learn the correction from standard 10-minute simulations is problematic, as yaw control time constants are too long and they may be rather site-dependent. Finally, the flow near the nacelle has been shown to be very complicated and sensitive to turbine characteristics [7]. Because of this complication, [1, 6] both suggest that a good solution could be to learn this correction using a nacelle-mounted lidar.

Some literature has explored the ability of nacelle-mounted lidars to accurately measure yaw misalignment for this purpose. Studies [8, 9] demonstrate using simulated and experimental data that a spinner-based lidar is capable of measuring yaw misalignment accurately (within a few degrees), even in highly turbulent flow.

In this paper, researchers from the National Renewable Energy Laboratory (NREL), Avent Lidar Technology (Avent), and Renewable NRG Systems investigated the use of a nacelle-mounted lidar for learning the previously mentioned correction function. An Avent Wind Iris lidar was installed on the two-bladed Controls Advanced Research Turbine (CART2). The turbine was then operated normally while recording lidar wind measurements. A bias was observed in the nacelle vane measurement, and a correction was determined. Next, the turbine was run for several months with and without the correction function applied. Findings indicated an improvement in yaw alignment and a resulting improvement in power capture. Finally, we considered the impact on turbine loads of making this correction and found agreement with predictions from the literature. The outcome of this study is a documented test campaign in which a lidar is used to find the yaw correction function and confirmation that applying of that function improved power production.

The remainder of this paper is organized as follows. Section 2 provides details regarding the turbine and lidar used in this study, as well as information on the location where this investigation took place. Section 3 reviews the field campaign that was conducted. Section 4 presents the study results and analysis and Section 5 provides the conclusions.
2. Turbine and lidar

In this study, a Wind Iris lidar from Avent was mounted to the CART2. The CART2 is an experimental controls research turbine, with a rated power of 600 kW, a hub height of 36.6 m, and a rotor diameter of 42.6 m. It has been extensively retrofitted for performing controls research and includes a custom, real-time control system, fully grid-decoupled torque control (type 4), and independent pitch control. The turbine also provides substantial sensing capabilities, including a dedicated met tower, as well as strain gauges and accelerometers located inside the turbine. Finally, the CART 2 has been used in numerous past studies, including an investigation on lidar-enhanced feed-forward pitch control [10].

The Wind Iris is a two-beam pulsed lidar, with the beams separated by 30 degrees. It provides wind speed and direction measurements at 10 simultaneous ranges in front of the turbine. For this study, the ranges were configured from 40 m up to 220 m at increments of 20 m, and the lidar sampling rate was set to 2 Hz. For each range, wind speed and direction was obtained from the projected wind speeds measured on each beam. The lidar tilt, roll, and yaw angles were aligned according to the nacelle. In the study, relative wind direction with respect to the turbine was measured using the 80-m range. This is also the approximate distance to the met mast, and additionally was found to be a good selection because the lidar beam spacing at this distance is approximately one rotor diameter. The CART2 with mounted Avent Wind Iris lidar is shown in Figure 1.

![The Avent Wind Iris lidar mounted on the CART2. Photo credit: Lee Jay Fingersh, NREL.](image)

Figure 1: The Avent Wind Iris lidar mounted on the CART2. Photo credit: Lee Jay Fingersh, NREL.

Finally, it is important to note some relevant details of the CART2 and its surrounding location at the NWTC in Boulder, Colorado. The NWTC is located near the foothills of the Rocky Mountains and has a highly turbulent inflow. This high turbulence can influence the process of learning a turbine’s power curve. Additionally, because the CART2 is a research turbine, it only operates during specific tests, and oftentimes there is more than one ongoing
test in process. As a result, it is not possible to collect as much data with a research turbine as can be collected from a normally operating turbine. We believe, however, that the data collected in this study is sufficient to support the positive conclusions of this paper.

The controllers used in this study are the “baseline” turbine controls developed previously for past CART2 research campaigns (see [11] for example). The pitch controller is a proportional-integrator (PI)-like control that regulates the rotor speed in above-rated winds. The torque controller operates in below-rated winds and follows a conventional optimal torque curve. The yaw controller, which is most relevant for this work, is illustrated in Figure 2.

Figure 2: Yaw control and correction (adapted from [5]).

Figure 2 shows the block diagram of the CART2 yaw control system. The yaw error (measured by the nacelle vane) is applied to two low-pass filters. The faster filter feeds into a formula that integrates the squared error (with the sign reapplied). When this accumulated error exceeds a certain threshold (selected so that 10 degrees of error will exceed the threshold after 10 minutes), the turbine will then yaw to a new setpoint, which is determined by a slow filtering of the yaw error, unless the setpoint is in an unallowed location. Figure 2 shows (in red) where the to-be-derived correction will be applied within the controller.

3. Field test campaign

3.1. Initial campaign

The initial phase of the campaign was to learn the nacelle vane offset function by running the turbine with the above described baseline controller while recording lidar data. This phase lasted for about 1 month in August and September of 2013 and yielded approximately 40 hours of operational data (again, because of the CART’s experimental operational plan it does not run continuously). At the end of this period, the mean offset between the lidar-measured yaw error and the nacelle-vane-measured yaw error was computed for each rotor speed. This comparison is shown in Figure 3a.

Based on the results shown in Figure 3a, the vane of the CART2 does not have a bias with a linear dependence on rotor speed. Instead, the behavior seems to be that once the turbine is operating (rotor speed is over 10 rpm), there is a scalar offset. Based on this initial data, an offset of 7.5° was estimated and is shown in Figure 3a as a blue horizontal line.

Figure 3b shows the same comparison as Figure 3a; however, using all the data collected that was not available when the offset was derived. Looking at this data, it is clear that a more substantial offset would have been appropriate (perhaps 9.5°), and the function is not linearly dependent on rotor speed.
Figure 3: Error between the nacelle-vane-measured wind direction and the lidar measurement. The plots show the mean value and a 95% confidence interval for 10-s averages per low-speed-shaft (LSS) rpm bin. The blue line indicates the selected offset value for correction.

Figure 3b also more clearly demonstrates the nature of the nacelle vane bias. At 0 rpm, when the turbine is off, there is an approximate 4° bias. When the turbine begins operating, this bias goes to approximately 9.5° and stays near that point across the rotor speed operation range. This is a fundamentally different behavior than what was observed on the CART3 in [1, 5], with its linear dependence on rotor speed. This is interesting, as the CART2 and CART3 are identical, with identical wind vanes, except the CART3 has been retro-fitted with a three-bladed rotor using different blade shapes. This finding attests to the difficulty of learning this bias through modeling.

In hindsight, because of this lack of linear rotor-speed dependence, it would have been more appropriate to produce an average of all the data regarding the offset between the nacelle-vane and lidar measurements without binning by rotor speed. Figure 4 indicates that this approach would have produced a better offset more quickly. In addition, Figure 4 shows that collecting about 100 hours of data would have provided sufficient data for statistical convergence.

3.2. Correction testing campaign
In the second phase of the study, we applied the correction learned in Section 3 to the yaw control as shown in Figure 2. We then collected data by first running the turbine with the yaw-error-corrected controller for a period of a month, and then for several months alternating between the original, or baseline, controller and the corrected controller. The amount of data collected is shown against time and by speed in Figure 5.

4. Data analysis and results
4.1. Data processing
The collected data, both from the lidar and the turbine sensors were processed as follows. For all the data that were gathered, “blocks” of data, with sizes of 10 s, 60 s, and 600 s, were extracted from the data collected when the turbine was operating normally. From these blocks, statistics such as mean values and standard deviation (e.g., of measured power output for this block) were
Figure 4: Estimates of scalar offset between the nacelle vane and lidar (with 95% confidence interval plotted as vertical lines) as data were collected; plotted against hours of collected data. The dashed red line indicates the point at which the offset was computed.

Figure 5: Amount of data collected (using 60-s blocks.)

computed. In total, we collected 66,696 10-s blocks (7.7 days), 10,960 60-s blocks (7.6 days),
and 957 600-s blocks (6.64 days).

In the remaining figures, the block size that was used is indicated in the caption, while the number of points per bin is indicated by the size of the marker at that point in the figure.

Figure 6 (on the left side) shows a comparison of the lidar-measured relative wind direction (yaw misalignment) for the baseline and corrected controllers by rotor speed in 1-rpm bins. For further comparison, the right side of Figure 6 shows the relative mean direction measured by wind vanes on the dedicated wind mast. Note that the calibration offset of the met mast vanes is determined visually using known landmark directions and is assumed to be accurate to only a few degrees, and so the offset between the red lines is likely caused by this calibration process. The figure indicates a clear improvement in yaw alignment using the lidar-derived correction. A similar trend and improvement is evidenced when using the reference mast, thereby validating the lidar wind direction measurements.

![Figure 6: Lidar and met-mast wind vane computed yaw misalignment using 10-s blocks plotted against low-speed-shaft (LSS) rpm, with number of data points per bin (N) indicated by point size. Note that the met-mast wind vane measurement does not rotate with the turbine as the lidar and nacelle vane do, so it was corrected using measured yaw position to produce this figure.](image)

4.2. Power capture

In Figure 7, power curves are derived for the base and corrected controllers and are computed using both 10-s and 600-s blocks. The 10-s blocks, although not standard, are useful because the CART2 test site is highly turbulent, and as a result, a 600-s bin will often include a wide
range of wind speeds. Some 600-s bins were observed to include 4 m/s to 22 m/s. This can, for example, cause the wind speed mean to be biased upwards when very high gusts are experienced, although much above-rated wind speeds contribute no extra power above rated power. Given enough time, these effects should average out, but the 10-s blocks are useful to more closely tie a given power output to the wind speed at that time with limited data. Additionally, during data collection, there were not many periods of high wind speeds that were collected for a full 10 minutes, making the 600-s block power curve sparse for higher wind speeds.

The power curves were computed using the wind speed that was measured by cup anemometers located at the dedicated met mast. Although it is possible to use the lidar for this purpose, the testing actually continued after the lidar was uninstalled, using the already determined correction function. The wind speed measurements were air-density-corrected using the equation:

\[ V_{\text{norm}} = V_{\text{meas}} \left( \frac{\rho_{\text{meas}}}{\bar{\rho}} \right)^{\frac{2}{3}} \]  

Where \( V_{\text{norm}} \) is the normalized wind speed, \( V_{\text{meas}} \) is the measured wind speed, \( \rho_{\text{meas}} \) is the measured air density, and \( \bar{\rho} \) is the average air density. The power measurement is the electrical power computed by the power electronics. To include the maximum amount of data, it was not limited to the yaw direction in that the met mast is upstream, which would have been a standard filter on the data.

Figure 7a shows that when the power curve is computed using 10-s blocks of data, an increase in power can be observed for the corrected controller, particularly in the near-rated wind conditions around 14 m/s. This increase is also evident at 14 m/s for 600-s bins; however, a lack of 600-s data for higher wind speeds causes noticeably incorrect results, such as a drop in power at 15 m/s.

If we assume that the trend in the 10-s power curves is accurate, then we can use the power curves to estimate the impact on overall energy output. We used the method for estimating annual energy production (AEP) with the standard reference wind speed distribution and a mean wind speed of 9 m/s from [12]. Doing these calculations for both the baseline and corrected power curves produces a predicted percent increase in AEP from using the correction function as 2.4%.

### 4.3. Loads analysis

In addition to the comparison of power capture, the CART2 also provides sensor data that can be used to compare the impact on loads by using the lidar-provided yaw correction. In this section, we look briefly at this effect.

In Figure 8, the loading values are presented for the two cases. Most of the bending and torsional loads are presented as 1-minute damage-equivalent-load computations [13], whereas the teeter angle, which is a measure of the movement of the rotor teeter, is presented via a standard deviation.

These results are consistent with available literature. Blade-flap bending increases somewhat below rated wind speed and decreases somewhat above rated wind speed. This response is consistent with the pattern observed in [14]. Tower fore-aft bending follows a similar pattern as it is related to the thrust and flap loads. Edgewise-blade bending and tower side-side bending increase a little bit, which is probably an effect of increasing aerodynamic torque and power. Low-speed-shaft torsion exhibits a small decrease, but the significance is presently unclear. Finally, teeter variations show a small increase. The overall impression is of minor variations of loading, which are consistent with expectations (greater power and torque should increase loads coupled with aerodynamic torque), and previous literature (that the flap and thrust loads would experience inverse changes above and below rated).

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Figure 7: Comparison of power curves with and without lidar correction factor applied, using 10-s and 600-s blocks. Points show mean while error bars indicate standard deviation. The size of the points indicates the number of samples in a given wind bin (N).

5. Conclusions
In this paper, we presented results from a study in which a nacelle-mounted lidar was used to improve the yaw alignment of an experimental turbine. Results demonstrated that the correction learned by the lidar significantly improved power capture compared to the uncorrected measurement of the nacelle vane. The impact of loading was considered and showed some positive and negative (generally small) impacts on loading, which were consistent with expectations and literature.

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References
[1] Kragh K A, Fleming P A and Scholbrock A K 2013 *Journal of Solar Energy Engineering* **135** 031018
[2] Madsen H A, Srensen N N and Schreck S 2003 *41st Aerospace Sciences Meeting and Exhibit*
[3] Fingersh L J 2014 Personal communication regarding unpublished analysis from NREL/NASA Ames Phase VI wind turbine study
[4] Hau E and Von Renouard H 2013 *Wind turbines: fundamentals, technologies, application, economics* (Springer)
[5] Kragh K A and Fleming P A 2012 *Proceedings of 50th AIAA Aerospace Sciences Meeting and Exhibit, American Institute of Aeronautics and Astronautics* (Nashville, TN: AIAA)
[6] Bossanyi E, Kumar A and Hugues-Salas O 2012 *Proceedings of the Science of Making Torque from Wind* (Oldenburg: EWE)
[7] Zahle F and Serensen N N 2011 *Wind Energy* **14** 271–283
[8] Kragh K A, Hansen M H and Mikkelsen T 2013 *Wind Energy* **16** 353–366
[9] Kragh K A, Hansen M H and Mikkelsen T 2011 *Proceedings of the 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition* (Orlando, FL: AIAA)
Figure 8: Comparison of certain loads for each controller using 60-s blocks. The points indicate the mean load, the error bars indicate the standard deviation and the size of the points number indicates samples per wind bin (N).

[10] Schlipf D, Fleming P, Haizmann F, Scholbrock A, Hofsaß M, Wright A and Cheng P W 2012 Proceedings of the Science of Making Torque from Wind (Oldenburg: EAWE)
[11] Johnson K E, Fingersh L J and Wright A D 2005 Controls advanced research turbine: lessons learned during advanced controls testing (National Renewable Energy Laboratory)
[12] Internaional Electrotechnical Commision 61400-12-1 ED. 1.0 2005. Wind turbines - Part 12-1: Power performance measurements of electricity producing wind turbines
[13] Hayman G J and M Buhl J 2012 MLife Users Guide for Version 1.00 (National Renewable Energy Laboratory)
[14] Kragh K A and Hansen M H 2013 Wind Energy