Field Test Results from Lidar Measured Yaw Control for Improved Yaw Alignment with the NREL Controls Advanced Research Turbine

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Field test results from lidar measured yaw control for improved yaw alignment with the NREL Controls Advanced Research Turbine

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This paper describes field tests of a light detection and ranging (lidar) device placed forward looking on the nacelle of a wind turbine and used as a wind direction measurement to directly control the yaw position of a wind turbine. Conventionally, a wind turbine controls its yaw direction using a nacelle-mounted wind vane. If there is a bias in the measurement from the nacelle-mounted wind vane, a reduction in power production will be observed. This bias could be caused by a number of issues such as: poor calibration, electromagnetic interference, rotor wake, or other effects. With a lidar mounted on the nacelle, a measurement of the wind could be made upstream of the wind turbine where the wind is not being influenced by the rotor's wake or induction zone. Field tests were conducted with the lidar measured yaw system and the nacelle wind vane measured yaw system. Results show that a lidar can be used to effectively measure the yaw error of the wind turbine, and for this experiment, they also showed an improvement in power capture because of reduced yaw misalignment when compared to the nacelle wind vane measured yaw system.

I. Introduction

Horizontal-axis wind turbines need to be aligned with the inflow wind direction to effectively capture power from the wind. This can be done passively with a wind turbine tail vane, but for most utility sized wind turbines, this is actively controlled by yawing the wind turbine based on a nacelle-mounted wind vane measurement. Theoretically, the power captured by a horizontal-axis wind turbine can be expressed through the following equations (from Ref. 1):

$$P_{max} = \frac{1}{2}\rho A_r C_P V_p^3 \tag{1}$$

$$V_p = V_0 cos\left(\theta_E\right) \tag{2}$$

Equation 1 shows that the maximum power (P_{max}) that could be captured depends on the wind speed perpendicular to the rotor plane (V_p), given the air density (ρ), rotor area (A_r), and the wind turbine power coefficient (C_p). In equation 2, the perpendicular component of the wind speed is expressed in terms of the free stream wind speed (V_0), and the cosine of the yaw alignment error (θ_E) between the turbine's yaw direction and the free stream wind direction. Combining these two equations implies that if there is a yaw error, the power is reduced by the cube of the cosine of the yaw error. However, results from empirical data

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have shown that the relationship could be cosine-squared instead of cosine-cubed.[2] In either case, a yaw misalignment reduces the power produced by the wind turbine.

Typically, the wind vane used to measure the wind direction is located on the nacelle of the wind turbine. For upwind machines, this means that the wind vane is located downstream of the wind turbine's rotor. Recently, experiments have shown that the rotor's wake can induce a bias in the wind vane measurement[1] and that the bias is turbine dependent as a different turbine produced a different bias from experimental results discussed in Ref. 3. This bias would result in a power loss due to the turbine's constant misalignment with the wind. Additionally, power losses have been observed in existing industrial wind farms.[4] These power losses are caused by wake interactions not wind turbine yaw misalignment. However, simulation work has shown that wake redirection is possible[5] and can be utilized in a wind plant to improve power production through wake redirection optimization.[6] To implement wake redirection in a controller, a particle filtering method was proposed in Ref. 7, where each turbine's capability to accurately measure the wind direction was key in the controller's ability to track the wind turbine wakes within a wind plant. These methods assume that the individual wind turbine is able to have good control of its yaw error from a good measurement of the wind direction, which is contrary to what has been been shown from field experiments.[1,3,8] If an accurate measurement of the wind direction could be made upwind of the turbine, the measurement would no longer be influenced from effects of the wind turbine, which would result in better control of the yaw error of the wind turbine. This in turn would result in better power production at an individual turbine level because of the reduction of yaw misalignment and better power production at the wind plant level when combined with the methods discussed in Refs. 5, 6 and 7.

In Refs. 1 and 3, the yaw misalignment issue is solved by determining a yaw bias correction function and correcting for it a priori in the yaw control system. In Ref. 1, a meteorological mast (met-mast) was used to collect wind direction data independent of the nacelle-mounted wind vane to compute the yaw bias correction function. However, experimental results in Ref. 9 show that as the wind turbine's yaw direction deviates from the met-mast wind turbine alignment, the correlation between the wind speed experienced by the met-mast and the wind speed experienced by the turbine diminishes. In Ref. 3, a lidar was mounted on the nacelle to collect wind direction data upwind of the turbine. Since the lidar yaws with the wind turbine nacelle, the measurement used to compute the yaw bias correction function is upwind of the rotor regardless of the turbine's yaw direction. Both of these methods hinge on the fact that once the yaw bias is known, it remains the same throughout all wind conditions for the lifetime of the wind turbine. If something were to change later, such as a degrading wind vane, or failing electronics, the bias would change, and the bias correction function would no longer be applicable. Instead, a lidar could be used to directly control the yaw of the turbine eliminating the need for a yaw bias function.

Figure 1: CART3 experimental wind turbine at the NWTC. Photo credit: Lee Jay Fingersh, NREL.

This paper presents field test results from a novel method in which a nacelle-mounted lidar was used to measure the wind direction upwind of the rotor plane and fed back to directly control the yaw direction. For this experiment, no yaw bias correction function was needed, since the lidar was used to directly control the yaw direction of the wind turbine. Increased power production was observed by using this method when compared to conventional nacelle-mounted wind vane measurement of the yaw error. The paper will first describe the wind turbine and lidar and then will discuss the yaw controller used for the experiment, explain the field implementation, give the results and analysis, and conclude with next steps.

II. Wind Turbine and Lidar Descriptions

Controls field testing has been done extensively in the past at the National Wind Technology Center (NWTC) at NREL located outside of Boulder, Colorado United States. Most of the controls field testing has revolved around the Controls Advanced Research Turbines, one of which is 2-bladed (CART2) and the other is 3-bladed (CART3). For this experiment, the CART3 was used. Figure 1 shows the CART3 and Table 1 presents some essential information about the turbine. The CART3 is a 600-kW variable-speed pitch-controlled turbine with a custom control system that facilitates simplified modifications to the controller for different research experiments. The CART3 has an extensive suite of sensors beyond what is typically installed with industrial turbines. This allows for highly customizable controllers as well as detailed analysis on loads, wind characteristics, and power performance of the wind turbine. Additionally, the CART3 has a dedicated met-mast located aproximately 86 meters upwind of the wind turbine from the predominant wind direction of 292°. The met-mast has instrumentation to measure the wind direction and wind speed at hub height, as well as the top and bottom of the rotor swept area.

Table 1: CART3 Turbine Specifications

Rotor Power	600 kW
Rotor Diameter	40 m
Rated Speed	37 rpm
Hub Height	36.6 m

Figure 2: Profile view of the ZephIR lidar mounted on the roof of the nacelle of the CART 3. Additionally the nacelle wind vane can be seen in the upper left of the picture. Photo credit: Lee Jay Fingersh, NREL.

The lidar used for this experiment was a continuous wave lidar developed by ZephIR Lidar. The lidar uses Doppler shifted backscattered light to determine the line-of-sight wind speeds from which horizontal wind speed and wind direction are derived. A summary of the Lidar specifications is given in table 2. The lidar was mounted on the top of the nacelle approximately 2 meters behind the rotor plane as seen in figure 2. The lidar measured 50 line-of-sight wind speeds in a 1-second circular scan. The half cone angle of the scan pattern was 15°, and the axis of rotation of the scan was aligned with the axis of the rotor in the yaw direction. The tilt angle of the scan axis was aligned to be horizontally level. The same lidar from ZephIR has been used in previous experiments and showed good results for power performance measurements.[10] For the installation on the CART3, the lidar's software settings were modified. Instead of providing 10-minute averages for power performance (as was previously done in Ref. 10), the lidar was set up to provide 10 Hz data in order to use it for real time control. Additionally, the lidar was focused such that the center of the scanning circle was located 58 meters in front of the lidar. With the lidar approximately 2 meters behind the rotor plane, this put the focus distance about 56 meters in front of the rotor plane. With the 15° half cone angle, this meant the lidar measured a circle with a radius of about 15 meters, or about 75% of the blade span. The focal distance was chosen so that the lidar measurement would be beyond one rotor diameter upstream to avoid any induction zone effects.[11] The wind direction measurement is limited to about ±45° from the scan rotation axis. This is partially due to the fact that the lidar is not able to determine the sign of the Doppler shift, and hence the lidar is not able to determine if the wind is travelling towards or away from the lidar. This issue is resolved by assuming that the lidar is always pointing towards the general wind direction, so the wind direction measurement is restricted to ±90°. A further restriction of ±45° is made due to low measurement quality when trying to measure line-of-sight wind speeds that are far from parallel to the general wind direction. Furthermore, to derive the wind direction from the line-of-site measurements, an assumption is made that there is no horizontal wind shear. This assumption needs to be made due to the cyclops dilemma that is further described in Ref. 12.

Table 2: Zephir Lidar Specifications

Beam Type	Continuous Wave
Scan Pattern	Circular
Number of Points per Scan	50
Scan Rotation Period	1 second
Half Cone Angle	15°
Lidar Focus Distance	58 m
Data Rate	10 Hz

III. Yaw Controller Overview

For this experiment, the yaw controller was modified from the one used in Ref. 13. Instead of computing a yaw bias as was done in Ref. 13, a switch was placed in the yaw controller so that the yaw error measurement could be switched from the wind vane measurement or the lidar measurement. The switch, as well as the rest of the yaw controller, is illustrated in figure 3. The controller using the wind vane measurement will be referred to as "nacelle vane yaw controller" throughout the rest of this paper, and the controller using the lidar measurement will be referred to as "lidar yaw controller."

The yaw controller was designed in an "on-off" manner. When the turbine is not currently yawing ("off"), the yaw controller is accumulating low-pass filtered yaw error signal that comes either from the wind vane or lidar, depending on the measurement switch (shown in red in figure 3). Once the accumulated error reaches

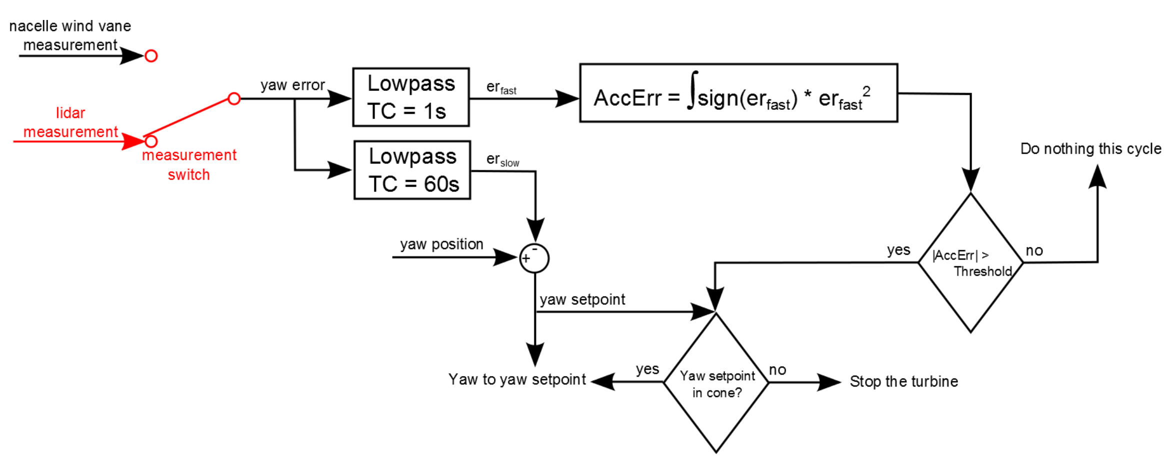


Figure 3: Block diagram (modified from Ref. 13) showing the logic for the CART3 yaw controller. The items indicated in red were added for the lidar yaw control experiment.

a certain threshold (chosen so that 10° of yaw error exceeds the threshold after 10 minutes), the controller decides whether or not to yaw depending on whether or not the new yaw setpoint is within the yaw limits of the turbine. While the turbine is yawing to the new setpoint ("on"), no yaw error is accumulated. Once the turbine has reached the new setpoint, the turbine stops yawing and begins to accumulate yaw error again.

IV. Field Implementation

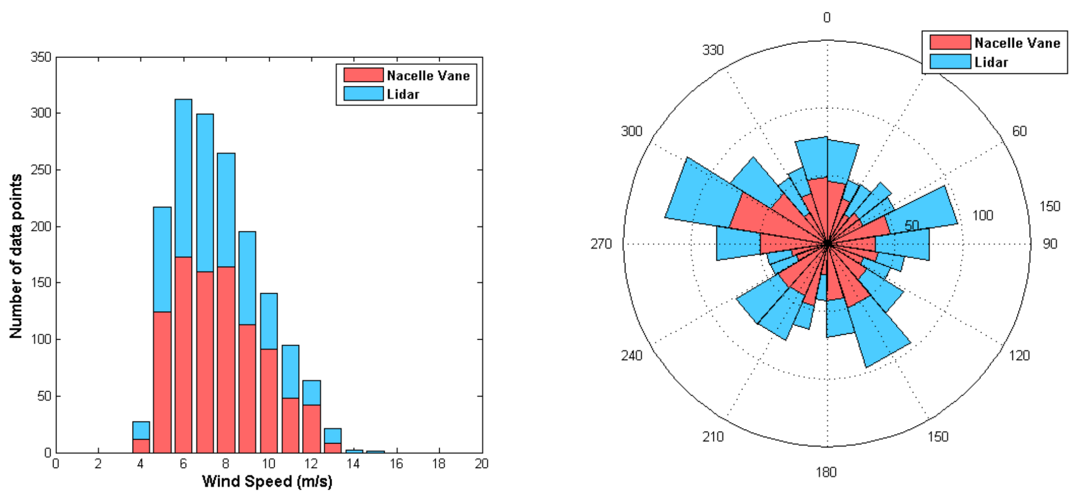
The modified yaw controller described in the previous section was implemented into the CART 3 controller. The wind turbine's torque controller was not modified from the baseline controller, which follows an optimal torque curve in below-rated winds. Additionally, the pitch controller was not changed from the baseline controller and uses a simple proportional-integrator (PI)-like control to regulate the rotor speed in above-rated winds. The baseline controller is based off of the controller described in Ref. 14.

Because the lidar only provides valid high-accuracy data for wind directions lying within ±45° of the scan axis, the lidar yaw error measurement was only used while the turbine was running. When the turbine was sitting idle (also known as "waiting for wind") or starting up, the nacelle wind vane was used to orient the turbine. This allowed for the wind turbine to be aligned with the general wind direction by the time it switched to normal running operation. With improvements to lidar technology, such as those discussed in Ref. 15, the lidar wind direction measurement could be expanded to the full ±180°. With that expansion, it would then be possible to use the lidar wind direction measurement all of the time, including waiting for wind and startup conditions.

Additionally, if the lidar was unable to provide a valid measurement for a given time step (determined by a separate quality flag signal provided by the lidar), then the controller would use the wind vane measurement for that time step. This safety check was implemented so the lidar would not cause the turbine to yaw abnormally because of invalid measurements, and it was thought to be a strategy that would be easily adopted in the wind turbine industry.

For this experiment, the data collection process ran from April to July 2014. The controller was automated to run on a two-hour cycle. The first hour used the nacelle vane yaw controller and the second hour used the lidar yaw controller. The cycle would then repeat itself after the second hour.

In all, about 60 hours of data was collected with the turbine running and sitting idle. After removing idle



(a) Wind speed distribution Plot

(b) Wind Direction distribution Plot

Figure 4: These histogram plots show the distribution of data points vs. the wind speed and wind direction for the operational field test data collected for this experiment. The red portion shows the data collected where the nacelle vane was used to control the yaw direction of the wind turbine, and the blue portion shows when the lidar was used to control the yaw direction of the wind turbine. This plot shows that the data collected between the two wind direction measurements was reasonably well balanced for all the data collected for this experiment.

and startup data, and transitions between the nacelle vane yaw controller and the lidar yaw controller, about 12 hours of operational data were collected using the nacelle vane yaw control signal, and about 9 hours of operational data were collected using the lidar wind direction yaw control signal. Figure 4a shows the wind speed distribution of the operational data, and figure 4b shows the wind direction distribution of the operational data collected for this experiment. It was seen that the data collected was reasonably balanced between the two wind direction measurements. For the analysis of the data, the raw time-series data were broken down into 45-second blocks of data, where one block represents the averaged values of the data from 45 seconds of continuous data. In some of the plots, "N" is given, and it refers to the number of data points used per bin. Additionally, error bars in the plots refer to 95% confidence intervals.

V. Results

To quantify whether or not the lidar improved the yaw alignment of the wind turbine, a comparison needs to be made between the turbine's yaw position versus the wind direction. However, because the wind direction is not explicitly known, comparisons were made with the wind direction measurements from the lidar, the hub height met-mast vane, and the nacelle-mounted vane to determine a general trend. Figure 5 shows the yaw misalignment of the wind turbine when compared to the lidar wind direction measurement, as well as the met-mast wind vane direction measurement, both as a function of the turbine's rotor speed. Each comparison shows similar results in that the nacelle-mounted wind vane yaw controller seems to have a 20° yaw misalignment, and the lidar yaw controller performs much better with a yaw misalignment much closer to zero. Another thing to note is that with the nacelle vane yaw controller, the yaw misalignment is not dependent on the rotor speed. This is in disagreement with what was found in Ref. 13, and is probably due to a new issue that was not present in 2011 when the data was collected for Ref. 13. This large difference, as well as the disagreement with what was found in Ref. 13 led the authors to explore what the source of the new error could be, and will be discussed later in the results section. In figure 5, no yaw bias correction function was applied. This was chosen so that the lidar measured yaw controller could be evaulated against a traditional nacelle vane measured yaw controller. Alternatively, a comparison could be made between a lidar measured yaw controller and a nacelle vane yaw controller with a yaw bias correction function applied. If the yaw bias correction function is reasonable, the comparison would then show that there is less yaw misalignment for the nacelle vane controller corrected by the yaw bias function.

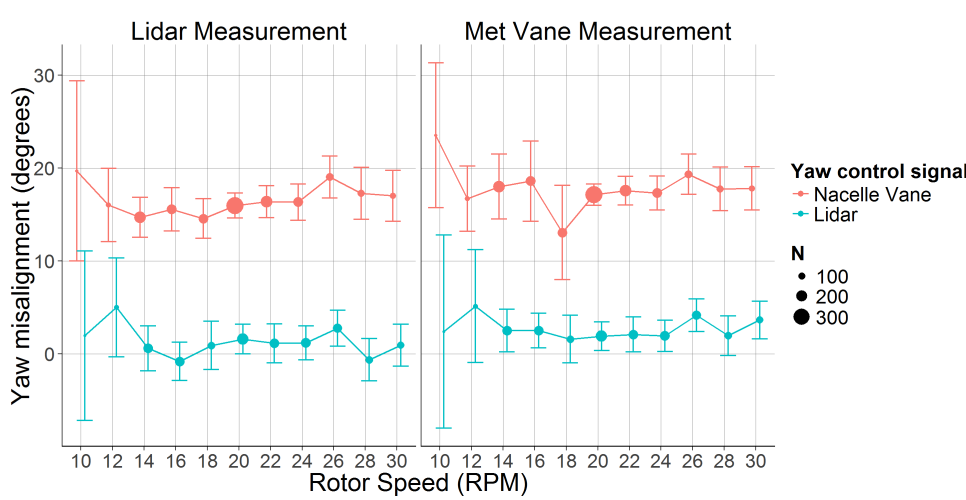


Figure 5: These plots show the wind turbine yaw misalignment as a function of rotor speed for the nacelle vane yaw controller (in red) as well as the lidar yaw controller (in blue). The left plot shows the yaw misalignment when compared to the wind direction as measured by the lidar, and the right plot shows the yaw misalignment when compared to the wind direction as measured by the met-mast wind vane. For the controller using the measurement with the nacelle vane, no yaw bias correction function was applied. If a yaw bias correction function was applied, then the yaw misalignment from the nacelle vane is expected to be lower.

To further verify that the lidar yaw controller was aligning the turbine with the wind direction better than the nacelle vane yaw controller, a power performance analysis was done. Figure 6 shows the power performance results from using the lidar yaw controller versus the nacelle vane yaw controller. It can be seen that in below-rated winds, compared to the nacelle vane yaw controller, the lidar yaw controller shows an improvement in power capture. There is more uncertainty at higher wind speeds because there is less data being collected at those wind speeds. This analysis shows that even without knowing the true wind direction, the observed increase in power capture should be due to better yaw alignment because the only difference between the two controllers is which sensor is measuring the wind direction. Hence, for this experiment, the lidar measurement of the wind direction proved to more accurately measure the wind direction than the nacelle wind vane.

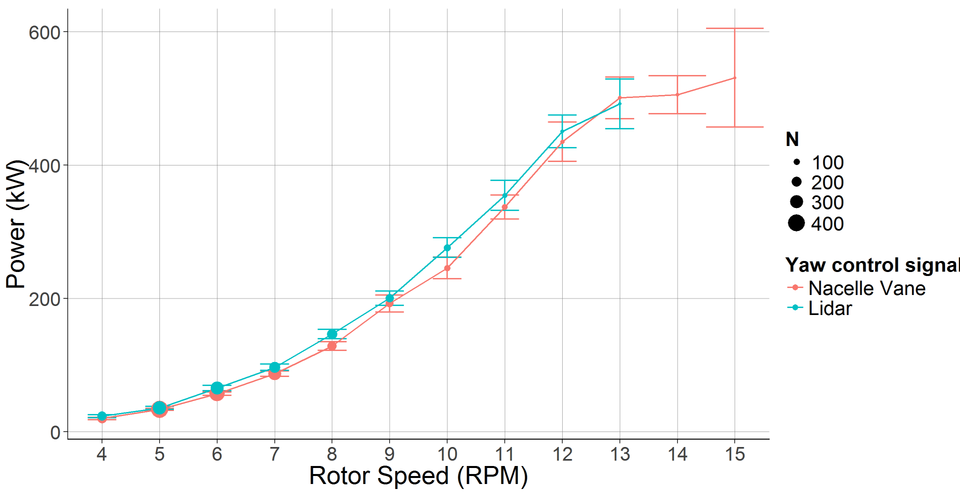


Figure 6: Power capture for different wind speeds using a nacelle vane yaw controller (red) versus a lidar yaw controller (blue). By using the lidar yaw controller, increased power capture was observed due to better yaw alignment with the wind direction.

The first step for finding out if there may be an issue with the nacelle wind vane having a such a large bias was to see the data in real time. After looking at the data, it seemed that the behavior was associated with whether or not the turbine was running. Figure 7 shows two signals taken from the time series data recorded in real time. The top signal shows the controller state, which is zero when the turbine is stopped, and then switches to one when the controller decides to start up to begin running. The bottom signal shows the nacelle wind vane measurement, which can range from -180° to +180° because it is in the nacelle frame of reference. When the controller switches from stopped to running, the nacelle vane signal becomes much noisier and has a bias, both of which are believed to be spurious and not an actual representation of the wind direction. The noise is not a large issue for the yaw controller because its decisions on new yaw set points are based on a slow 1-minute filtered average of the signal, which removes much of the noise. However, the bias is an issue because it will cause the turbine to settle on a yaw position that is not aligned with the inflow wind direction. The root cause of this issue with the nacelle wind vane could be due to one or several things, including electrical noise or failing electrical components.

The time-series data showed that further analysis was needed to determine whether or not the nacelle wind vane being impacted by the turbine running was true for all of the data collected. Figure 8 shows the nacelle wind vane offset as a function of rotor speed when compared to the lidar (on the left) and the met-mast wind vane (on the right). The blue line indicates when the controller was stopped, which has some data where the rotor speed was above zero due to the rotor slowing down after a shut down command was issued. The red line indicates when the controller was running, which is after the turbine was started up. This figure shows that the nacelle vane has a bias that is associated with the turbine running that is not as present when the turbine is stopped. Figure 7 together with figure 8 show that the bias is not induced by the wind flow, but rather is an electrical noise issue since the bias is introduced into the signal in figure 7 almost immediately after the turbine starts up when the rotor is still stationary.

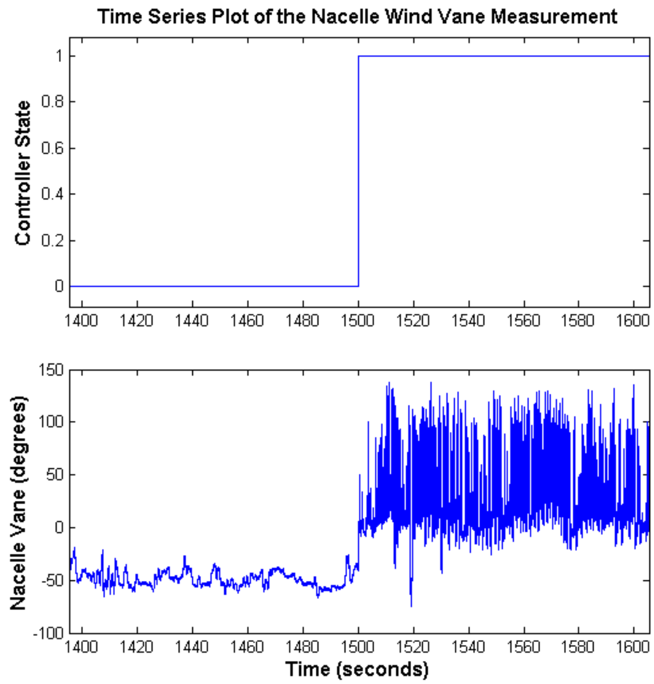


Figure 7: These plots show an example of what was found by looking at the nacelle wind vane signal real time data. The top plot shows the controller state, where zero is when the turbine is stopped, and then is switched to one where the controller starts up the turbine. The bottom plot shows the corresponding nacelle wind vane signal, where after the turbine starts up, significant noise as well as a bias is introduced into the nacelle wind vane signal.

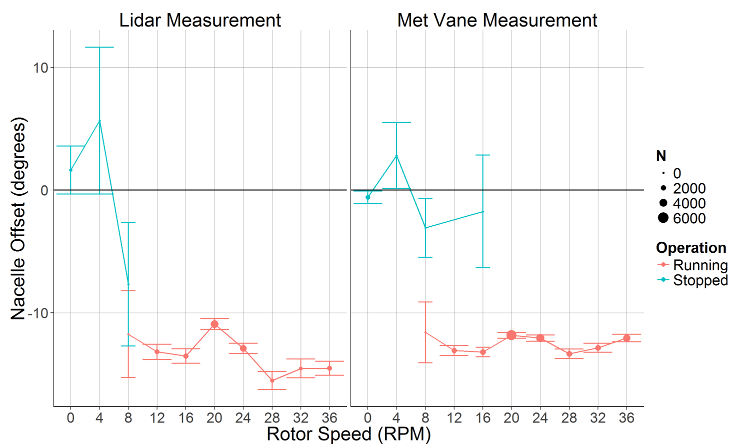


Figure 8: These plots show the nacelle wind vane offset versus the rotor speed when compared to the lidar wind direction measurement (left), or the met-mast wind vane measurement (right). The blue line indicates when the turbine was stopped, and the red line indicates when the turbine was running. It is evident that the offset is closer to zero when the turbine is stopped, and a bias exists when the turbine is running.

VI. Conclusion

This experiment has shown that a wind direction measurement from a nacelle-mounted forward looking lidar can be used to effectively control the yaw position of a wind turbine. Additionally the conventional nacelle wind vane system installed on the wind turbine was shown to have a bias in it. The bias was found to be induced when the turbine was operating and was much less noticable when the turbine was stopped. The lidar was able to provide a more accurate measurement of the wind direction, which led to an improvement in turbine yaw alignment, as well as power performance. These improvements were made with the limited lidar range of $\pm 45°$ and using the nacelle wind vane to point the turbine in the general wind direction before starting the turbine up. If the lidar measured yaw controller were compared to a nacelle vane controller with a yaw bias correction function, then the improvements would probably not be as large. However, if no yaw bias function is known, then using a lidar measured yaw controller could show improvement in yaw misalignment and power production. Additionally, if a yaw bias correction function is known the nacelle vane measurement could shift over time due to damage or degradation leading to an incorrect yaw bias correction function. Further research could be done to compare the differences between a lidar measured yaw controller, and a nacelle vane measured yaw controller with a yaw bias correction function.

Using this method for improved yaw control could be combined with other possibilities for improved wind turbine performance. For example, this method could be combined with feed-forward collective pitch control strategies that could potentially be used to reduce turbine loads. Simulations that expand this research to the wind plant level indicate that a highly accurate wind turbine yaw controller could redirect wakes for improved wind plant performance. By using a lidar wind direction measurement, a highly accurate wind turbine yaw controller is more achievable than using a traditional nacelle-mounted wind vane.

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