Field Test Results of Using a Nacelle-Mounted Lidar for Improving Wind Energy Capture by Reducing Yaw Misalignment

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Lidar-Enhanced Controls Research at NREL

• NREL, working collaboratively with research partners, has developed, analyzed, and field tested lidar-enhanced strategies for improving:
  o Pitch control
  o Torque control
  o Yaw control
  o Active power control.

• Several research campaigns ongoing

• Focus of this presentation is yaw control.
Note on References

• Most of the results to follow are more fully described in available publications, or else articles under review

• Contact paul.fleming@nrel.gov to request references and for an explanation of slides and further details.
Motivation

• Modern commercial turbines use active yaw control, typically based on measurements from nacelle-mounted wind vanes

• Static errors in measurement can occur as a result of:
  o Rotor wake
  o Complex flow from nacelle
  o Environmental impacts on the wind vane
  o Poor calibration or installation.

• Yaw misalignment can lead to reduced power production.

Photo by Lee Jay Fingersh, NREL
Yaw Misalignment Research Campaigns

• **Campaign one:**
  - Learned and applied nacelle vane correction function
  - Partnered with:
    - Avent Lidar Technology
    - Renewable NRG Systems (RNRF).

• **Campaign two:**
  - Directly used lidar as control signal for yaw controller
  - Partnered with:
    - ZephIR Lidar.
Turbine Descriptions

• **Controls Advanced Research Turbines (CARTs) 2/3:**
  - Hub height of 36.6 meters
  - Rotor diameter of 42.6 meters
  - Power rated at 600 kilowatts
  - Two or three blades.

• **Extensively instrumented:**
  - Dedicated meteorological (met) mast
  - Strain gauges
  - Accelerometers.

*Photo credit: Andrew Scholbrock, NREL*
Research Campaign One

• NREL/Avent/RNRG collaborated on uses of lidars for improved turbine control
• Phase one used the lidar measurement to determine yaw misalignment correction function running the baseline controller
• Phase two collected data with and without the correction function (two hours per cycle).
Lidar Specifications

• Avent Wind Iris
  o Sample rate of 2 hertz
  o Pulsed lidar
  o Ten measurement ranges
  o Two horizontal beams
  o Half-angle of 15°
  o Calibrated to the rotor axis to within 0.1°.

Illustration courtesy of Samuel Davoust, Avent Lidar Technologies

Photo by Lee Jay Fingersh, NREL
Yaw Controller Schematic

\[ \text{AccErr} = \int \text{sign}(e_{r_{\text{fast}}}) \cdot e_{r_{\text{fast}}}^2 \]

Lowpass
TC = 1s

Lowpass
TC = 60s

yaw error
precomputed offset

Do nothing this cycle

\[ |\text{AccErr}| > \text{Threshold} \]

yes

no

Yaw to yaw setpoint

Yaw setpoint in cone?

yes

no

Stop the turbine

Yaw setpoint

Yaw position

\[ e_{r_{\text{fast}}} \]

\[ e_{r_{\text{slow}}} \]
Measurement Campaign

Red line indicates point when offset was computed

Group chose a 7.5° initial offset after 40 hours of data were collected.

A better choice would have been a ~9.5° offset if all data from the experiment had been used.
Yaw Correction Compared to Met Mast

![Graph showing yaw correction comparison between Lidar and Met Mast](image-url)
Results: Power Improvement

Annual energy production estimated to be increased by 2.4% for a 7.5° offset.
Results: Error Function

Error bars indicate 95% confidence interval, points with large confidence interval not shown for neatness.
Research Campaign Two

- CART3 mounted with ZephIR lidar
- Direct use of lidar signal in yaw control.

\[ \text{AccErr} = \int \text{sign}(e_{\text{fast}}) \times e_{\text{fast}}^2 \]

Photo by Lee Jay Fingersh, NREL
Results: Power Improvement

![Power Improvement Graph](image)

- **Power (kW)** vs **Rotor Speed (RPM)**
- **Number of data points**:
  - 100
  - 200
  - 300
  - 400
- **Yaw control signal**:
  - Nacelle Vane
  - Lidar
Results: Error Function

![Graph showing nacelle offset against rotor speed for Lidar and Met Tower operations. The graph compares running and stopped operations with error bars indicating variability.]
Results

• In this case, vane appeared to have had a fault occurring in one direction
• Rotor-induced bias toward that direction furthered the impact
• However, calibration with turbine offline appeared to have been correct

• Paper to be presented at AIAA 2015.
Conclusions

- Lidars have been shown to be capable of resolving errors in yaw calibration by:
  - Learning a correction function
  - Applying the lidar signal directly.
Further Research with Yaw Control

• Ongoing research at NREL and the Delft University of Technology is exploring control strategies for wind plants
• One topic of interest is the use of yaw control for the redirection of turbine wakes to optimize overall plant power
• Accurate yaw alignment detection is a must.
Further Research with Lidar-Enhanced Controls

• NREL has collaborated with other research centers and lidar manufacturers on the use of lidars for enhanced:
  o Pitch speed control
  o Torque control
  o Active power controls.
Lidar-Enhanced Pitch Control

• Several test campaigns completed, and several more ongoing

• Use lidar wind speed preview information as feedforward input to pitch controller
  o Improve speed regulation
  o Reduce turbine loads.

Photos by David Schlipf, Stuttgart Wind Energy (top left), and Lee Jay Fingersh, NREL (top right, bottom left, bottom right)
Results: Pitch Control

Rotor Speed

Tower Bending

Figure courtesy David Schlipf, Stuttgart Wind Energy

Photos by Lee Jay Fingersh, NREL
Pitch Control

• Recent demonstration with Stuttgart Wind Energy (SWE) and a ZephIR lidar mounted on CART3 showed successful application of lidar feedforward control.
Pitch Control

- Ongoing campaign on the CART2 with an Avent five-beam demonstration lidar and DNV-GL is yielding promising results.

Figures courtesy of Avishek Kumar and Ervin Bossanyi, DNV-GL
Active Power

• Current research in active power controls investigates the use of wind energy in the provision of grid services

• In study, use lidar measurement of wind speed to maintain a fixed power overhead

• Field test with CART3 and Avent five-beam demonstration lidar.
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Thanks for Your Attention!

Photo by Dennis Schroeder, NREL

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