August 2016

Minutes
IEA WIND Task 32 Workshop #2 on

Optimizing Lidars for Wind Turbine Control Applications

Date: July 5th 2016
Venue: Boston Marriott Copley Place, Boston, MA, USA
Immediately preceding the 2016 American Control Conference
Workshop leader: Eric Simley, Envision Energy

Agenda Overview

8:30	Welcome/Introduction to IEA Wind Task 32
8:45	Introduction to workshop
9:00	Introduction to lidar-assisted control
9:30	Requirements and objectives of lidar systems for control purposes from the wind turbine manufacturers' perspective
10:15	Coffee break
10:30	Design considerations and constraints for lidar systems for control purposes from the lidar industry's perspective
11:30	Roundtable discussions on lidar-assisted control objectives and current barriers for lidar for wind turbine control
12:30	Lunch (Fogo de Chao)
1:45	Sources of lidar wind speed measurement error for control applications
2:15	Exercise 1: Investigating how lidar parameter and scan pattern choices impact measurement quality
3:15	Coffee break
3:30	Exercise 2: Investigating how lidar measurement error, measurement filtering and wind speed time-of-arrival uncertainty impact controller performance
4:30	Roundtable discussions on lidar system optimization for control applications
5:30	Workshop wrap-up and formulation of next steps, including preparation of the final report
6:00	End of workshop
7:30	Dinner (California Pizza Kitchen)

Participant List

Name	Country	Institution
Alan Wright	USA	NREL
Andrew Scholbrock	USA	NREL
Bin Wang	China	Goldwind
Bryan Williams	USA	GE
Cédric Arbez	Canada	TechnoCentre Éolien
Chris Slinger	UK	ZephIR
Conner B. Shane	USA	GE
Daniel Zalkind	USA	University of Colorado Boulder
David Schlipf	Germany	SWE University Stuttgart
Dhiraj Arora	USA	GE
Eric Simley	USA	Envision Energy
Evan G. Osler	USA	Renewable NRG Systems
Florian Haizmann	Germany	SWE University Stuttgart
Guilin Zhou	China	Goldwind
Hirokazu Kawabata	Japan	Advanced Industrial Science and Technology
Holger Fürst	Germany	SWE University Stuttgart
Jan-Willem van Wingerden	Netherlands	TU Delft
Justin Creaby	USA	Siemens
Kathryn Johnson	USA	Colorado School of Mines
Lei Liu	China	Goldwind
Lucy Pao	USA	University of Colorado Boulder
Matthieu Boquet	France	Avent
Michael Hind	USA	Siemens
Nikolas Angelou	Denmark	DTU Wind Energy
Nobuki Kotake	Japan	Mitsubishi Electric Corporation
Paul Fleming	USA	NREL
Pierino Bonanni	USA	GE
Raach Steffen	Germany	SWE University Stuttgart
Róbert Ungurán	Germany	University of Oldenburg
Romain Goussault	France	IFPEN
Roozbeh Bakhshi	USA	University of Maryland-College Park
Sachin Navalkar	Netherlands	TU Delft
Shumpei Kameyama	Japan	Mitsubishi Electric Corporation

Minutes

Welcome/Introduction to IEA Wind Task 32 (David Schlipf, University of Stuttgart) [8:30]

- David welcomes everybody
- Round of introduction
- David introduces the IEA Task 32

Introduction to Workshop (Eric Simley, Envision Energy) [8:50]

- Eric introduces the workshop

Introduction to lidar-assisted control (Andy Scholbrock, NREL) [9:00]

- Andy gives an overview on lidar-assisted control, including collective pitch feedforward-control as well as yaw-control
- Lidar is like spinach – it makes wind turbines strong! ;-)
- His two cents for lidar design: Lifting points and bore sight
- Vision for the future: Lidars everywhere!

Requirements and objectives of lidar systems for control purposes from the wind turbine manufacturers' perspective

1) Conner Shane, GE [9:40]

- We need to know the value of the technology
- You start to know a lot about a system if you put it on a turbine at different sites across the world
- Lidar based control value: Load – reducing cost / Power Capture – increasing AEP
- Extreme Event Detection is less in focus because the 50-year-gust is no longer in the standards (moving from IEC ed. 2 to IEC ed. 3 load certification)
- Main focus is on continuous feed-forward control (fatigue loads)
- Lidar requirements for turbine control:
    - cost (they are still too expensive), not only initial costs but 20-year life time costs
    - performance expectations: access to raw data, GE wants to do the signal processing, availability, geometry/configuration, self-diagnostics
    - Lidars are applied in harsh environments: vibrations, weather, industrial service environment
- Nacelle-mounted seems to be acceptable, GE hasn't gone a lot into spinner-mounted
- Availability is very important, influenced by blade blockage, atmospheric conditions, for control a "x number of valid measurements during the last 3s" has been looked at
- Wind resource knowledge challenge (impact of real wind coherency and wakes on Lidar based estimation)

2) Bin Wang, Goldwind [10:08]

- Lidars are used for site assessment and all the "traditional" applications
- But also for research of wind flow, wake and so on
- Lidar is like the headlights of a car to the wind turbine
- GW's most interest: increase energy yield, reduce loads, …
- Questions:
    - Can we get more accurate wind field measurements rather than just a few points? How? If not, what is the exactly relationship between them?
    - Is the Lidar measurement steady and reliable for all kind of atmospheric conditions?
    - What is the reasonable lifetime of a Lidar (degradation and failures)?

- If we meet heavy fog or clean air?
- Any other applications to benefit from Lidar?
- Cost!

Design considerations and constraints for lidar systems for control purposes from the lidar industry's perspective

1) Matthieu Boquet, Avent [10:40]

- Avent dedicated to Lidar-assisted Turbine Control, developing integration program with OEMs involving engineering, science and services, taking into consideration volume and unit costs
- Multiple academic and industrial projects since 2011
- Example of collaborative roadmap with OEMs: Technology Case, Product Development, Validation, Industrialization
- Necessity of high-quality metrology for turbine control: accuracy and precision, availability and redundancy, selectivity, and robustness.
- Important to educate the market about lidar-assisted control benefits
- But debunking myths around what lidar can/can't do and true characteristics needed, avoiding industry disaffection because low-end technology would not have provided the said promises
- Considering the real-life environmental conditions: avoid discrepancies between research community and practical aspects raising from OEM while both should be compatible
- Collaboration between OEMs, Lidar providers and research organizations is a key success factor

2) Shumpei Kameyama, Mitsubishi and Hirokazu Kawabata, AIST [11:06]

- Using a center beam (3 beams) is beneficial for the calculation of the wind speed
- How much measurement quality is needed for turbine control? (Time resolution, spatial resolution, measurement availability
- Everything impacts the cost! (Measurement distances, …)

3) Chris Slinger, ZephIR [11:26]

- Experience in lidar-assisted control: first trial in 2003, patent in 2003, lots of campaigns going on since then
- Aiming at a 10 year service interval
- No drift in calibration anticipated
- Detailed system and user requirements would be beneficial (location of integration, communications protocols, information needed by the control system, processing balance, availability, reliability, redundancy, system diagnostics and status monitoring, maintenance needs)
- Barriers: turbine manufacturers need to be sure of the benefits lidar can bring (also retrofit market), still insufficient evidence to adopters for cost/reliability/atmospheric conditions/operation in complex flows/achievable availability

4) Questions from participants:

- Do the costs scale with production volume? -> Yes, of course
- What about the measurement quality in different atmospheric conditions? -> All lidars are subject to different atmospheric conditions. Maybe a tradeoff between availability and accuracy (for control more towards availability?) can be found?

Roundtable discussions on lidar-assisted control objectives and current barriers for lidar for wind turbine control (small group discussions) [11:40]

- Eric introduces the small group discussions
- Question 1: What are the control objectives that lidar optimization should be considered for?
- Question 2: What are the barriers preventing the widespread use of lidars for control?

Group	Question 1	Question 2
1	• overall: Energy and Loads • WT & WF • grid connections • availability + reduce measurement errors • robustness, easy to install • standards, RP • self-adjusting • Performance matrix for Control	• cost-benefit question unsolved • question on availability open • TRL too low • difficult to access quality
2	Top Line: Lower the cost of wind energy • Feed forward collective pitch control for load reduction • Individual Pitch Control – maybe? • Improved Yaw Alignment • Less need to calibrate nacelle wind vane • Measure turbine performance • Extreme Event Mitigation • Detect if turbine is waked • Detect low level jet, atmospheric conditions	• Physical size • Lidars are retrofit onto turbines not integrated into design • Need for high data availability • Low availability with low aerosol • depends on test site • Reliability • Lidar cost ➔ needs to by its way onto the wind turbine • No good cost model yet for lidar savings on LCOE • Scaling Studies 500kW ➔ 5MW • Competition from other cheap sensors (spinner sonic anemometer)
3	• **YAW:** ⊕ Simpler lidar • 2 beams, low sample rate - Requires there to be a problem **COL PITCH:** - More complicated ⊕ Value to all turbines **GRID:** Short Fore- or Nowcasting Operation Ground-Based?/Nacelle/Mount Range **O&M:** Detect High-Duty/SCADA **IPC:** Detect Shear/ Partial Wake Most Complex **WFC:** Flow-field reconstruction Large spatial + Temporal Resolution	• COST ○ Volume ○ Relative/Absolute ○ Maintenance ○ Design/Retrofit ○ Ultimate • Availability • Adaption • Certification/Design • Proof of Benefits

(Note that the items listed here do not necessarily represent a consensus of all workshop participants.)

Sources of lidar wind speed measurement error for control applications (Eric Simley, Envision Energy) [14:15]

- Eric gives an introduction to lidar measurement quality and sources of error for this

- The performance of a combined feedforward/feedback control system can be conveniently analyzed in the frequency domain. Here the example of blade pitch control for generator speed control is used.
- Using the simplification that the wind turbine dynamics can be represented by a linear transfer function, the power spectrum and variance of generator speed can be easily calculated using the power spectra of the rotor effective wind speed and lidar measurements as well as the cross power spectrum between the two variables
- The variance of generator speed can be minimized by using an optimal measurement filter instead of the raw lidar measurements
- Measurement coherence determines the minimum achievable measurement error and generator speed spectrum and is therefore a useful function for assessing lidar measurement quality
- The rotor effective wind speed and lidar measurement power spectra as well as the measurement coherence can be calculated using a frequency domain wind field model
- Wind evolution is included in wind field models using a longitudinal spatial coherence model
- Rotor effective wind speed can be calculated by incorporating the radially dependent aerodynamic properties of the rotor, but to simplify the analysis, it can be treated as the rotor disk average of the longitudinal wind speed
- Line of sight measurement errors are significant when the angle between the lidar beam direction and the longitudinal wind direction is large. Larger beam angles mean that the transverse and vertical wind components contribute more to the line of sight measurement, reducing the coherence with the longitudinal component of interest.
- For a nacelle mounted lidar, line of sight errors decrease as preview distance increases, but wind evolution errors increase. This leads to an optimal preview distance where error is minimized.
- The number of points in the scan pattern has a large impact on measurement coherence. The coherence bandwidth of the measurements can increase by roughly an order of magnitude when a perfect rotor disk average is used instead of a single forward staring lidar.
- The spatial averaging along the lidar beams present in lidar measurements can be helpful because it spatially averages the wind speeds more, similar to how the rotor disk averages the wind speeds
- In the induction zone upstream of the rotor, the wind speed will be reduced relative to the freestream and the wind direction will change slightly due to the wind inflow “expanding” around the rotor. The decrease in wind speeds can cause some uncertainty in the time-of-arrival of the measured wind at the rotor plane, which should be addressed by the control algorithm. However, a large eddy simulation based study shows that the presence of the induction zone does not cause a noticeable decrease in measurement coherence. But more work should be done to learn more about how the induction zone impacts measurement quality.

Exercise 1: Investigating how lidar parameter and scan pattern choices impact measurement quality (group exercise, leader: Eric Simley, Envision Energy) [15:15]

- Eric introduces exercise 1
- The exercise showed how a frequency domain wind field model including wind evolution can be used to optimize a lidar scan pattern
- The optimal scan radius and preview distance of a circularly scanning lidar that minimize mean square measurement error for a particular set of wind conditions were found
- Questions from participants after exercise 1: How well do these theoretical results compare to reality? According to David in general the field-testing show good agreement with the theory. One big problem is the wind evolution – this needs to be examined more.

Exercise 2: Investigating how lidar measurement error, measurement filtering and wind speed time-of-arrival uncertainty impact controller performance (group exercise, leader: Holger Fürst, SWE, University of Stuttgart) [16:15]

- Holger introduces exercise 2
- The exercise showed that
  - ...designing a feedforward controller assisting a basic collective pitch feedback controller assuming perfect wind preview is relatively simple: only the static pitch curve is needed.
  - ...a feedforward controller can have negative impact in comparison to a feedback only case if no filter and timing correction is used.
  - ...the best filter is found closed to the analytic transfer function from exercise 1.
  - ...the best timing correction is found by buffering the signal by the preview time (distance divided by mean wind speed) minus the delay from the filtering.
  - ...the feedforward controller based on the optimized trajectory from exercise 1 achieves significantly better reduction of the rotor speed variation compared to the staring case.
  - ...the analytic spectra fit very well to the estimated spectra from the time simulations.

Roundtable discussions on lidar system optimization for control applications (small group discussions) [17:00]

- Eric introduces to the second small group discussions
- Question 1: What are the design suggestions that can mitigate the identified barriers?
- Question 2: What are the design suggestions to optimize lidars for the identified control application?

<table>
<tr><th>Group</th><th>Question 1</th><th>Question 2</th></tr>
<tr><td>1</td><td colspan="2">• open-source virtual Lidar catalogue + cost model
• flexible research Lidars for field testing
• more advanced wind field model
• Lidars cost models that identify design drivers
draft guidelines for standard</td></tr>
<tr><td>2</td><td colspan="2"><u>Data Availability</u>
1. Adaptive Lidar ⇆ Weather Conditions
2. Use other WT systems to inform about lidar confidence
<u>Reliability</u>
1. Accelerated life testing during Lidar development
2. Incorporate Lidar Maintenance into standard schedules
3. Redundancy, Hot swap
<u>Cost</u>
• wind turbine based design
• understanding of cost benefit relation</td></tr>
<tr><td>3</td><td><u>COST:</u> Clear Requirements to get to volume
• cover Range of turbines
• Regular Maintenance w/o extra climbs
• Modular? / Easy Replacement
• Good Cost Model
<u>Avail.:</u> Spinner Mount
<u>Adaption:</u> Greater Cross-Knowledge / for control design</td><td>• Assess theory coherence before building
• Robust Optimization
• Real Time Capability
• Adaptability</td></tr>
</table>

(Note that the items listed here do not necessarily represent a consensus of all workshop participants.)

Workshop wrap-up and formulation of next steps, including preparation of the final report (group discussion) [17:50]

- Eric wraps-up the workshop
- Minutes will be uploaded to the workshop website, together with the exercise solutions and the slides from the presentations
- There shall be a workshop report compiled, where everybody is asked to contribute. It can be found on Google Docs (https://goo.gl/A5zs9q) and the organizers of the workshop will prepare a framework. This report might lead to Recommended Practices at the end of phase 2.
- A follow-up workshop can be organized during the second year of the task. If anybody would be interested in doing so, please talk to Eric or David
- Feedback from participants:
  - Pretty good, what was squeezed in the available time
  - If there would have been more time, more presentations would be nice
  - It is useful to choose a specific topic and work out on this instead of dealing with all
  - Very valuable was the mix of participants of the workshop
  - Everybody is fine with sharing their email-addresses
  - Alan (NREL) suggests a lidar-control campaign where we can do things better than in the past (learn from mistakes)

Thank you to everybody for organizing as well as participating in the workshop!