An Adaptive Data Processing Technique for Lidar-Assisted Control to Bridge the Gap between Lidar Systems and Wind Turbines

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I. Introduction

For wind turbines, the wind is the energy source as well as the main disturbance to the wind turbine control system. This has to balance competing control objectives: increasing the energy yield while reducing the structural loads. However, traditional feedback controllers are only able to react to the disturbance of the inflowing wind field after it has already impacted the turbine. With the recent development of lidar technology, the information about incoming disturbances can be made available ahead of time.

At initial field testing on the two- and three-bladed Controls Advanced Research Turbines (CART2 and CART3), a collective pitch feedforward controller was able to reduce the rotor speed variation [1], [2]. However, this reduction cannot be directly converted into a reduction of the levelized cost of energy (LCOE). Thus, one of the long-term research challenges identified by the European Academy of Wind Energy is the transformation into measurable benefit of lidar-assisted control [3]. A first study show a LCOE reduction of 6.5% for large offshore wind turbines [4].

One of the major obstacles due to the multi- and interdisciplinary character of the problem is a gap of knowledge: On the one hand, a thorough understanding of lidar measurement principles and limitations is mandatory for providing usable signals to the control system. On the other hand, detailed knowledge about wind turbine dynamics and controls are necessary to determine, which signals can be used for preview control. Since lidar and turbine manufacturer typically only know about their own branch, this gap can be closed by a joint project between industry and research institutions.

A consortium of NREL, SWE and the lidar manufacturer Avent Lidar Technology started to test advanced lidar-assisted control on the CART2 in January 2015. A new adaptive data processing technique independent from lidar and turbine control software and hardware was developed during this campaign. The improved setup and the combination of lidar- and turbine-specific knowledge enable a comparison of the rotor-effective wind estimates from turbine and lidar data. With a cross-correlation calculated in real-time, the lidar estimate can be aligned with the turbine's reaction via a Graphical User Interface (GUI). The feedforward control action can be applied to the turbine with the desired preview time which improves the overall control performance.

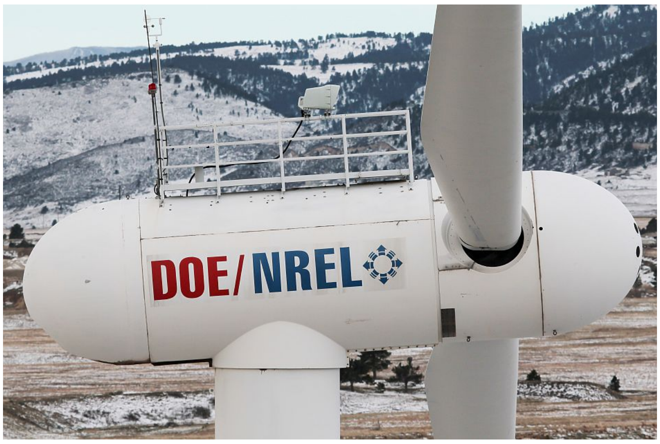

Fig. 1. The Avent 5-Beam installed on the nacelle of the CART2 at the NWTC. Photo by Lee Jay Fingersh, NREL.

II. Approach

In this section, the structured code development and new hardware setup are presented.

A. Structured Code Development for Lidar-Assisted Control

The code development for lidar-assisted control is structured in 5 stages:

1) *Feedforward Controller Development*: Assuming perfect wind preview, the feedforward controller is first tested with the Simplified Low Order Wind turbine (SLOW) model [5] with only 2 degrees-of-freedom (rotor and tower motion), see Fig. 2 (left). In this case the simulation model is identically with the controller design model and the control performance should be as desired. Then, the same wind is used in simulations with an aero-elastic model (FAST [6]) to test the robustness of the controller against model uncertainties.
2) *Data Processing Development*: The FAST model is disturbed by a turbulent wind field. A lidar simulator [7] is used to scan the wind field. The data is condensed to an estimate of the rotor-effective wind speed, filtered and transferred to the feedforward controller. The data processing can be evaluated by comparing the correlation between the lidar estimate and the real rotor-effective wind speed to a correlation model [8], [9]. Simulations are done over the full operation

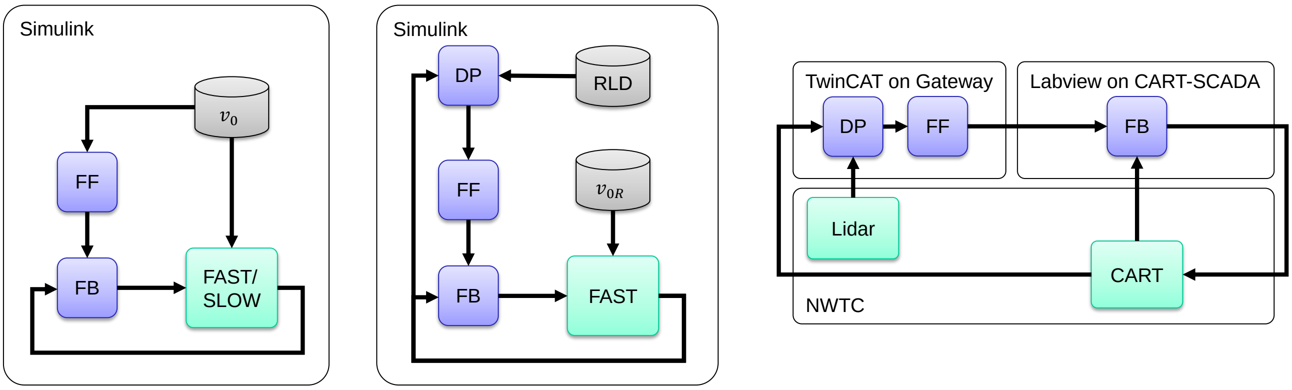

Fig. 2. Code development. Stage 1 (left): Simulation within Simulink with perfect wind preview; the rotor-effective wind v_0 disturbs the turbine and the feedforward controller (FF) is designed to assist the feedback controller (FB). Stage 4 (center): Hybrid Simulations within Simulink; the rotor-effective wind speed from turbine data v_{0R} and simultaneous measured raw lidar data (RLD) are used to adjust the data processing (DP). Stage 5 (right): Field Testing; the DP and FF are compiled for TwinCAT on the Gateway and the FB for Labview on the CART-SCADA.

range to test the robustness of the controller against measurement uncertainties.

3) *Development Real-Time Environment*: The data processing and the feedforward controller are compiled to be used within a real-time capable frame (TwinCAT) on a separate computer (referred in this work as "Gateway"). The same simulations from Stage 2 are done and thus allow a direct verification of the real-time environment.
4) *Hybrid Simulations*: Effects such as the wind evolution can be included [10] in simulations, but effects such as measurement errors and changing lidar data quality are difficult to simulate. Thus, the approach of the Hybrid Simulations [11] is used to adjust the lidar data processing and feedforward controller: The rotor-effective wind speed is extracted from real turbine data [12] and together with simultaneously measured lidar data used for simulations, see Fig. 2 (center).
5) *Field Testing*: Finally, the Gateway is connected to the lidar and the turbine controller, see Fig. 2 (right).

The approach has several advantages:

- The feedforward controller, the data processing and the real-time environment are developed independently. Thus, the data processing can be combined with different feedforward controllers.
- Each stage has a defined goal. This helps to develop several controllers in parallel.
- The code is developed in the control-engineer-friendly Simulink environment and is organized in one single library. Thus, adjustments can be directly transferred to other stages.

B. Hardware Setup for Lidar-Assisted Control

The CART2 located at the National Wind Technology Center (NWTC) is a 600 kW turbine heavily instrumented. A control system (CART-SCADA) was developed and implemented in LabVIEW by NWTC engineers running at 400 Hz containing a DLL compiled from the Simulink-based feedback controller.

The Avent 5-Beam pulsed system is installed on the nacelle of the CART2 and measures at 10 distances in front of the rotor. At each distance, 5 line-of-sight measurements are taken sequentially within 1.25 s and are transferred to the CART-SCADA via an Ethernet connection in real-time.

The data processing and feedforward controller are realized on the Gateway, a deterministic, real-time capable industrial PC, which is connected to the CART-SCADA via an Ethernet connection. The lidar data are condensed into an estimate of the rotor-effective wind speed. Additionally, the Gateway receives turbine data including rotor speed, blade pitch angle, and rotor shaft torque to obtain the rotor-effective wind speed. The Gateway provides its feedforward update signals to the CART-SCADA and the CART-SCADA can independently choose whether or not use the signals providing robust operation.

A separate computer connected to the gateway visualizes the processed data and offers way to directly interact with the Gateway via a GUI. Further, the feedforward control action (blade pitch, generator torque, desired rotor speed) are compared to measured data. Additionally, the software provides the possibility of adjusting parameters. This capability is used for the online-cross-correlation described in the next section.

III. Online Calculation of Cross Correlation

The feedforward control inputs are calculated based on the lidar estimate of the rotor-effective wind speed and sent to the CART-SCADA with an adjustable preview time before the wind disturbance reaches the turbine. This timing is crucial and the lidar estimate needs to be aligned with the rotor-effective wind speed from the turbine data. The preview time of the lidar estimate is based on Taylor's Frozen Turbulence Hypothesis and calculated by dividing the measurement distance by the mean wind speed. Changes in the preview can be due to the changing impact of the induction zone or inaccuracies in Taylor's hypothesis or the measurement distance.

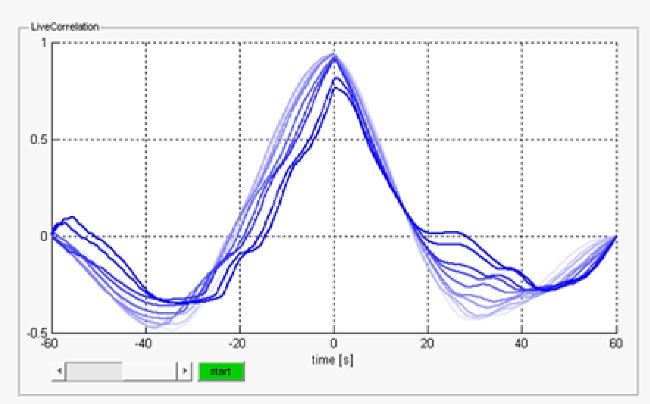

Fig. 3. Cross-Correlation between the lidar and turbine estimate of the rotor-effective wind speed over the last 10 s: Newest (dark blue) and oldest (light blue) data.

On the Gateway, the timing is evaluated online calculating the cross-correlation between the rotor-effective wind speed from lidar and turbine data. The normalized cross-correlation gives a measure of the similarity of the estimation and the timing of the estimation. An example of the online cross-correlation over the last 10 seconds is given in Fig. 3. The timing can be adjusted manually by shifting the lidar preview via the GUI and the changes can be observed in real-time.

During the ongoing field testing, an offset of 1 s was identified and corrected.

IV. Conclusion and Outlook

In this work a solution is presented which allows the data processing and feedforward control to be independently calculated of the lidar system and the turbine controller. This setup allows robust operation of the wind turbine and intensive calculations on time scales different from the feedback control loop.

Further, the setup provides the possibility to determine not only the rotor-effective wind speed estimate from the lidar data which is used for lidar-assisted control, but also of the rotor-effective wind speed from the turbine data. With both signals an online-cross-correlation is computed and visualized allowing an adjustment of the timing of the lidar-assisted control. This improves the performance of the feedforward controller.

In future work, the setup will be extended by an automated adjustment of the timing and filtering, once the method has been proven to be robust. The Gateway will be used for advanced feedforward controllers such as the flatness-based approach [13] and Nonlinear Model Predictive Control [14], [15], [16].

V. Learning Objectives

1) How can lidar systems and turbine control systems be connected for lidar-assisted control?
2) How can the wind preview from a lidar system be aligned with when it will impact the turbine under changing conditions?
3) How can the lidar data processing be adjusted interactively without interfering with the turbine operation?
4) What framework is simple, effective, and control-engineer-friendly for developing code which can be used for simulations and field testing?

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