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Field Testing of Flatness-Based Feedforward Control on the CART2

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[2]National Renewable Energy Laboratory
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Wind Europe Summit 2016
September 28
Hamburg, Germany

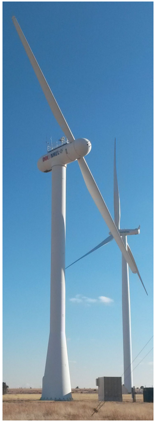
WindForS
Wind Energy
Research Cluster

SWE
Stuttgart Wind Energy
@ Institute of Aircraft Design

Motivation

How can we increase the TRL of lidar-assisted control?

- adjust lidar data processing to control [EWEA 2015]
- test baseline feedforward for full load [EWEA 2015]
- test advanced feedforward control for transition region



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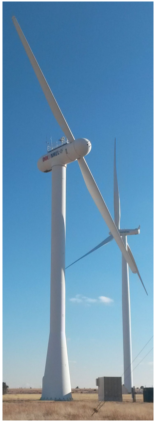
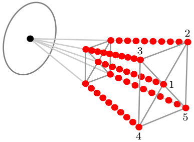
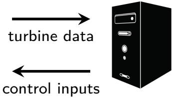
- CART 2, 42.7 m rotor
- CART-SCADA: feedback(SWE) & supervisory(NREL)
- Avent 5-beam lidar: 5 points in 1.25 s, 10 range gates







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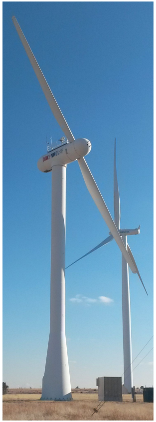

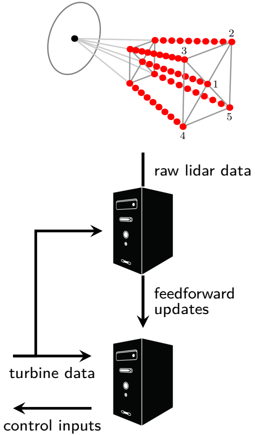

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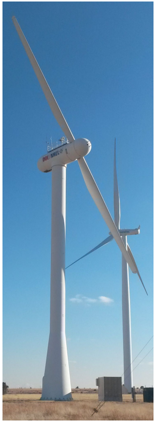

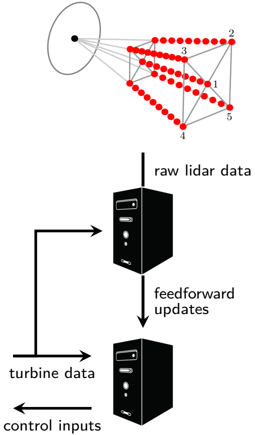

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- How can we realize a lidar-assisted feedforward controller in the transition region?
- What are the lessons learned from this field testing campaign?

Content

Controller Design

Differential flatness

- flatness is a system property: system inputs can be expressed by the flat output and its derivatives
- flatness-based control usually used for set point changes
- reduced wind turbine model is flat with flat output rotor speed Ω and tower displacement x_{T}

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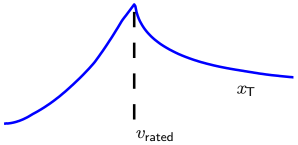

Tower EQUILibrium Accommodation (TEQUILA)

- tower and rotor trajectories are planned online based on wind preview
- uses collective pitch and generator torque feedforward update

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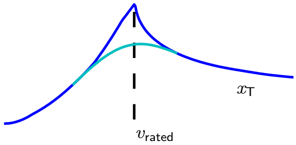

Tower EQUILibrium Accommodation (TEQUILA)

- tower and rotor trajectories are planned online based on wind preview
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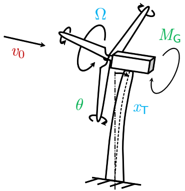
- minimizes tower motion during transitions between partial and full load

Design of Flatness-Based Feedforward Controller

Based on inversion of nonlinear 2 DOF model!



M_G	generator torque
θ	pitch angle
Ω	rotor speed
x_T	tower displacement
v_0	rotor-effective wind

Original wind turbine model

- inputs: M_G and θ
- outputs: $\Omega, \dot{\Omega}, x_\mathsf{T}, \dot{x}_\mathsf{T}, \ddot{x}_\mathsf{T}$
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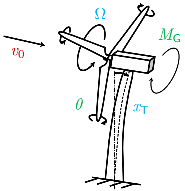

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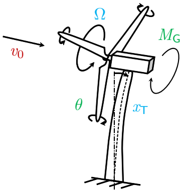

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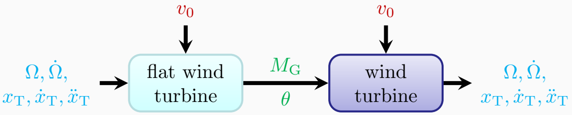
Now we can directly impose the turbine's dynamics!



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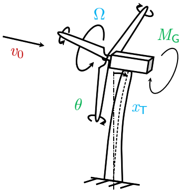

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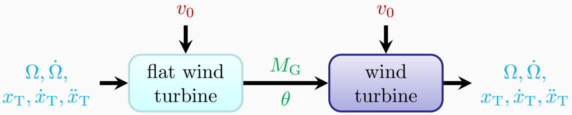
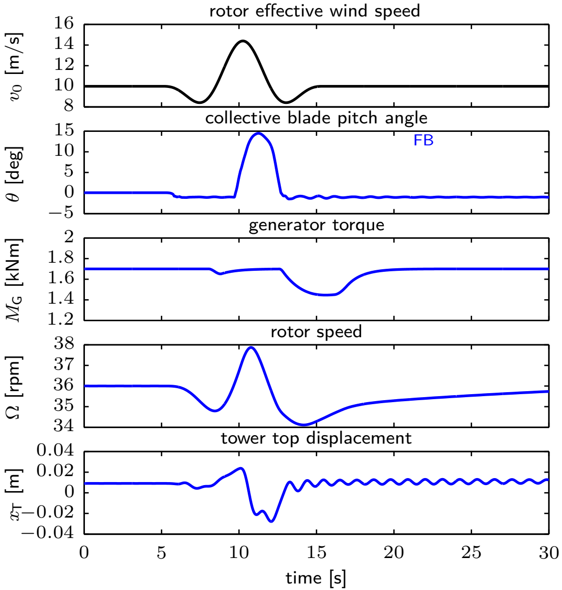
Now we can directly impose the turbine's dynamics! ... But how???



- trajectories for rotor and tower motion
- considering actuator constraints

$\rightarrow$ static curves + 7 parameters for dynamics

Simulation Study with Perfect Wind Preview



Environment

- full FAST model of CART2
- EOG at rated wind speed
- perfect wind preview assumed

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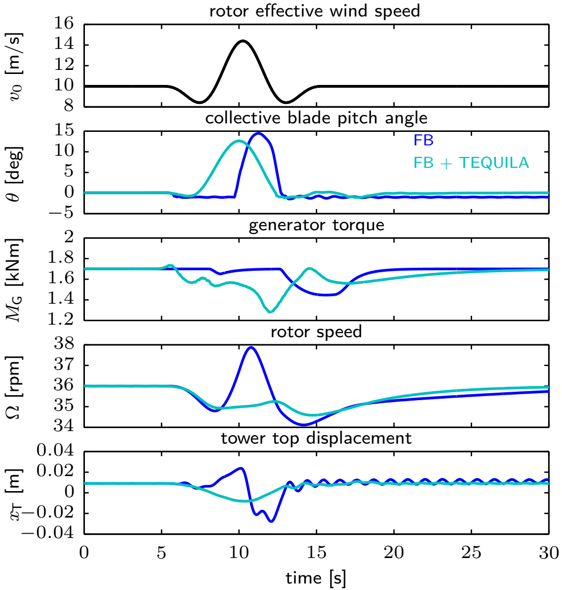

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- coordinated control behavior of collective pitch and generator torque
- rotor and tower motion reduced at rated

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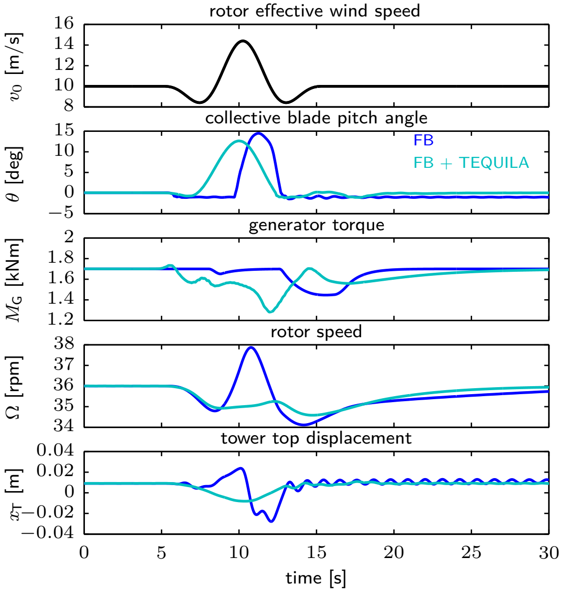

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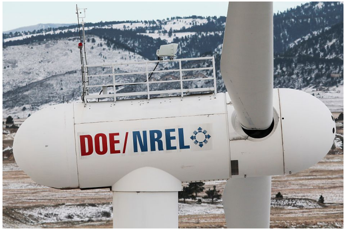
Adjustments for lidar-based preview

Trajectory planning needs to deal with:

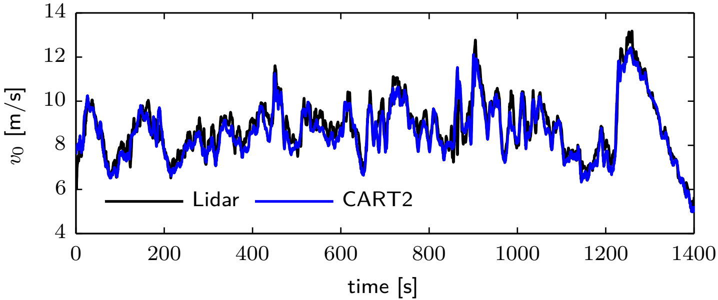
- measurement and model uncertainties
- delays in measurements and actuators

Comparing Lidar and Turbine



Rotor effective wind speed signals

- from turbine data and dynamic model using torque balance
- from raw lidar data using wind field reconstruction methods



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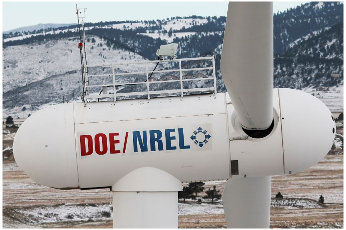
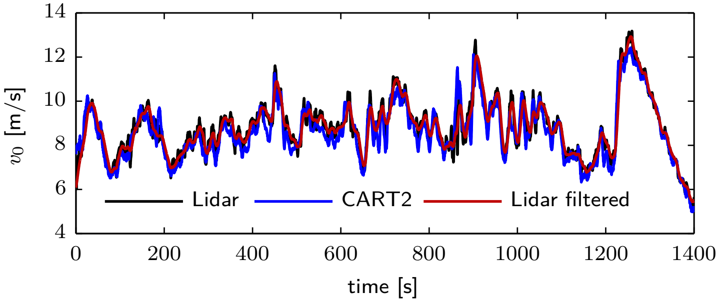




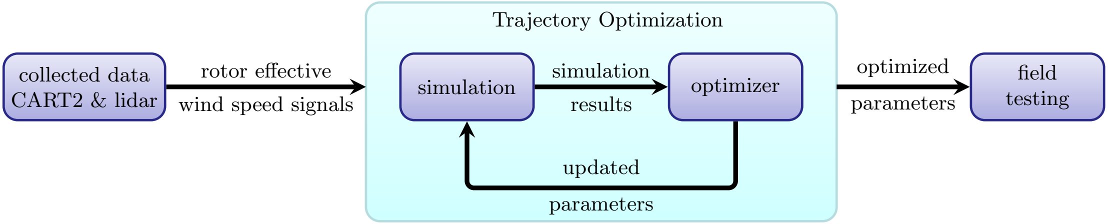
Comparison over time

- larger trends similar
- smaller details differ

→ we need to filter out uncorrelated frequencies

→ done by 2 parameters of trajectory planning

Tuning Flatness-Based Controller via Hybrid Simulations



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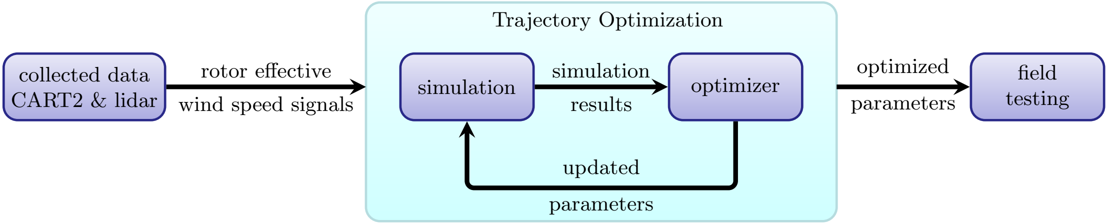
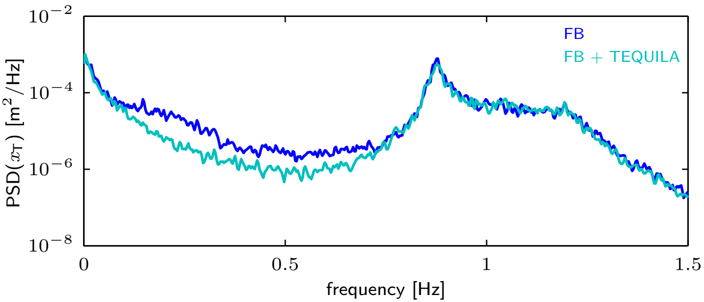


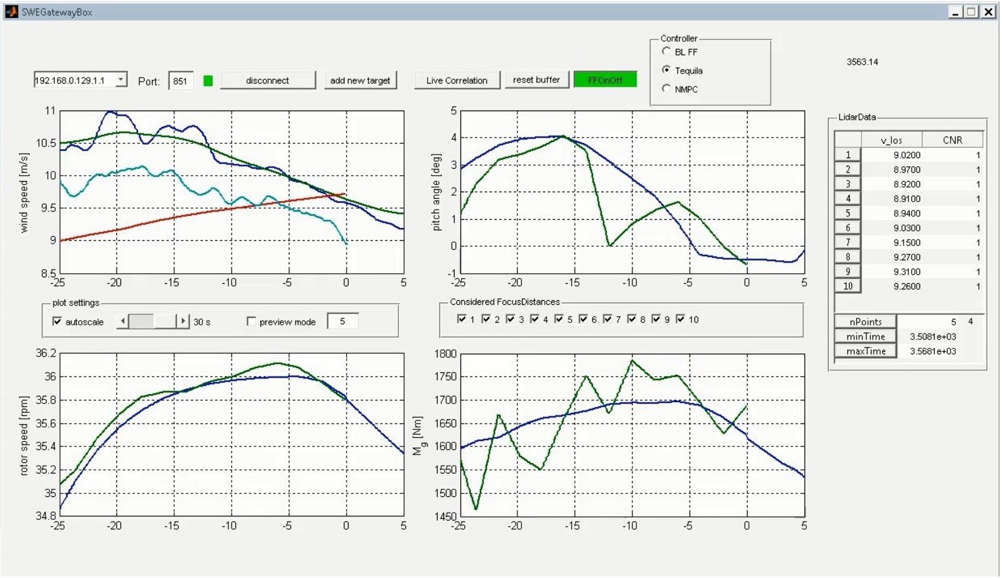


Trajectory optimization

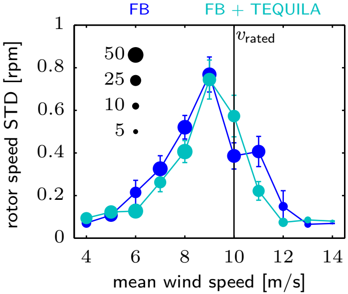
- 5 free tuning parameters
- cost = pitch activity + DEL (tower & shaft) - energy yield
- reduction of tower motion at low frequencies as expected

→ ready for field testing

Visualization of Data Processing on Gateway



Field Testing Results



Rotor speed regulation

- overall improved
- higher variation at v_{rated}

- 8 hours of data compared across 45-second chunks by NREL

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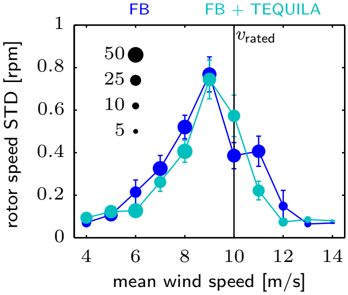

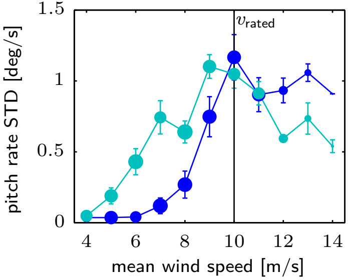

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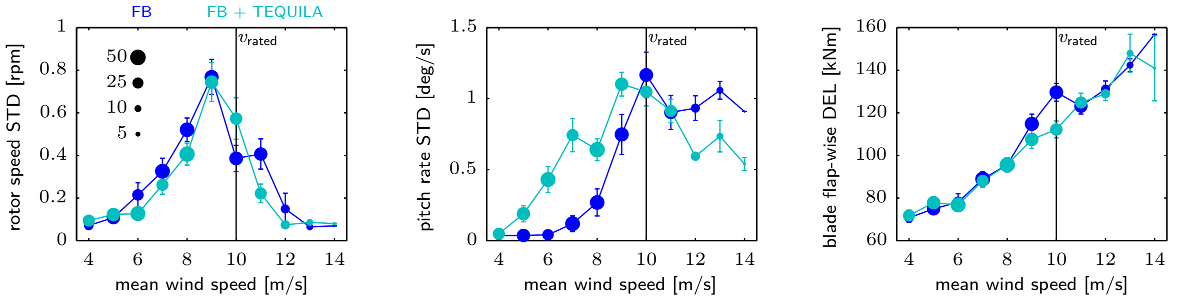

Rotor speed regulation

- overall improved
- higher variation at v_{rated}

Pitch activity

- more action below v_{rated}
- less action above v_{rated}

Blade loads

- reduction at v_{rated}
- not much effect elsewhere

- 8 hours of data compared across 45-second chunks by NREL

→ results in principle positive, but more testing necessary

Conclusion

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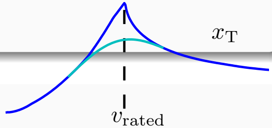

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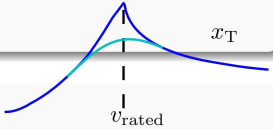

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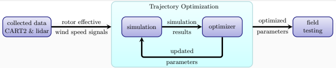
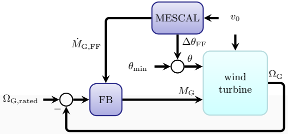


... but we need to re-think the concept!

- highly dependent on feedback controller and very sensitive to wind speed offset
- tuning of trajectory planning is tedious and only optimal for recorded data
- independent real-time capable system (Gateway) between lidar and turbine is very helpful!

Outlook



Multivariable extension based on simplified calculations [Schlipf, ACC 2016]

- linear feedforward control update of generator torque and pitch angle only in transition region
- can be combined with collective pitch feedforward control above rated wind speed
- avoids online trajectory planing by fixing motion, only one tuning parameter

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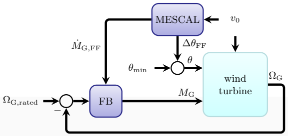

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Cooperation within IEA Wind Task 32 “Lidar”

Workshops to identify and mitigate barriers to the use of lidar:

- optimizing lidars for wind turbine control applications (June 2016)
- guidelines on how to use lidar in the load verification & certification process (2017)
- explore the benefits of lidar-assisted control for the cost of wind energy (2018)

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Thank you for your attention!

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