A Tutorial on Lidar-Assisted Control for Floating Offshore Wind Turbines

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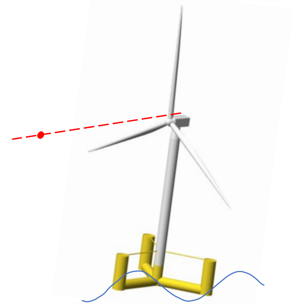
Motivation Lidar-Assisted Control for Floating Offshore Wind Turbines

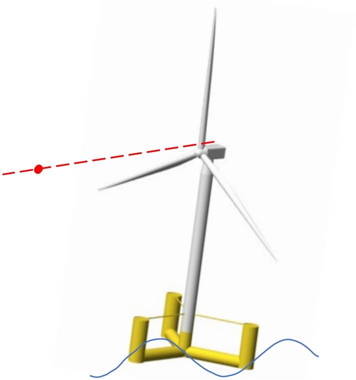


- wind is main disturbance to large floating turbines
- conventional control reacts after impact
- lidar technology provides wind preview
- better control performance is expected
- benefits proven for onshore wind turbines
- for floating wind turbines even more benefits can be expected due to more dynamic behavior

Objectives

- How can we integrate lidar signals into the controller of a floating wind turbine?
- How can you contribute to this exciting development?

Content



Floating Offshore Wind Turbine Control

[University of Maine]

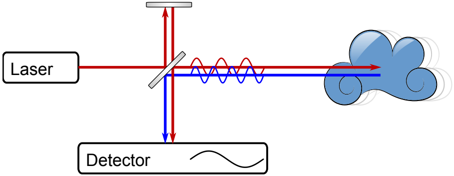
Challenges

- potential instability due to blade pitch controller ("negative damping") [1]
- standard offshore turbine with blade pitch angle and generator torque as only actuators
- strong impact of wind loads due to current trend of semi-submersible and large turbines

Reference design

- University of Maine's generic Volturn-US concrete semi-submersible [2]
- 15MW wind turbine, rotor radius $120\,\mathrm{m}$, tower-top mass $990\,\mathrm{t}$

Lidar Technology



[Goldwind]

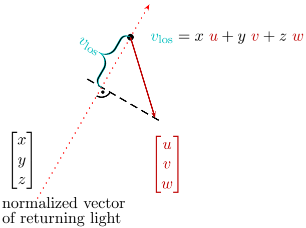
LIght Detection And Ranging

- uses optical Doppler effect
- measures speed of aerosols

Nacelle-based Lidar systems

- used for power performance testing, load verification and turbine and farm control
- $>$1000 onshore wind turbines (>3 GW) running with LAC [3] (Goldwind supported by sowento)

Lidar System Modeling

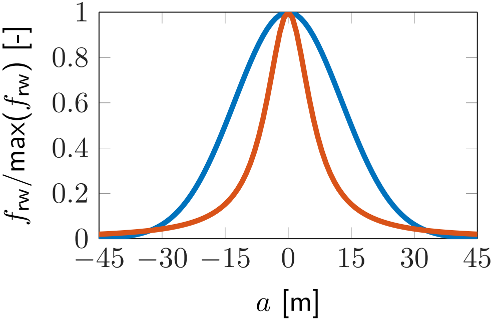


Point measurement model for estimation

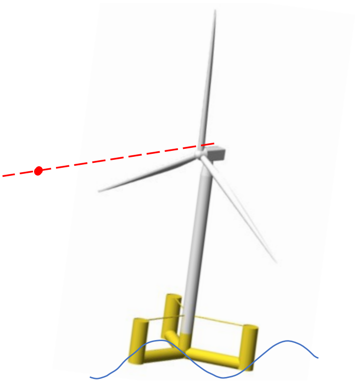
- only component in laser beam direction measured
- per convention positive, if towards lidar system
- → projection of wind vector on normalized laser vector
- if moving: $v_{\text{los}} = x\ (u - \dot{x}_{\text{L}}) + y\ (v - \dot{y}_{\text{L}}) + z\ (w - \dot{z}_{\text{L}})$

Volume measurement model for simulation

- $v_{\text{los}} = \int_{-\infty}^{\infty} (x\ u + y\ v + z\ w)\, f_{\text{rw}}(a)\, \mathrm{d}a$
- pulsed: constant over distance
- continuous wave: increasing with distance^2



Implementation Overview

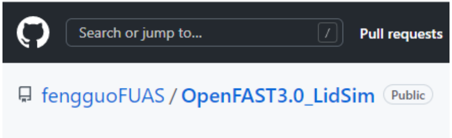


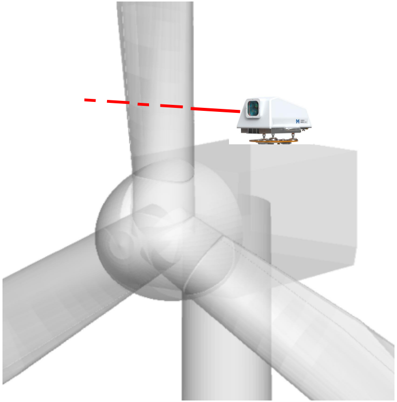
What is needed to realistically test LAC for FOWTs?

- aero-hydro-servo-elastic tool with a lidar simulator
- conventional feedback controller for comparison
- lidar data processing to convert raw lidar data into useful wind preview signals
- feedforward controller, MPC or similar to make use of wind preview signals
- robust implementation (EXE and DLLs) to handle complexity and to be more modular
- use cases showing the benefit of LAC

Main idea: provide a starting point to advance the development!

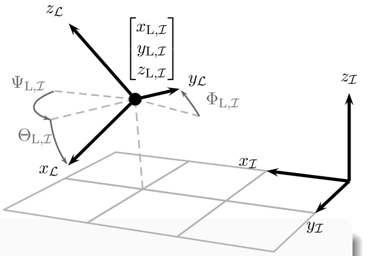
OpenFAST and Lidar Simulation





- OpenFAST: an Open-source software for calculating turbine aero-elasto-hytro-serco dynamics, written in FORTRAN.
- A new module "LidarSim" is integrated into OpenFAST version 3.0 [4] including
  - user defined trajectory
  - lidar probe volume measurement
  - nacelle motion
  - wind evolution
  - blade blockage
  - adjustable data availability
- Source Code and executable available on GitHub

Lidar-Data-Processing for Floating Lidars



Measurement Equation

$$v_{\mathsf{LOS}} = x_{\mathcal{I}}(u_{\mathcal{I}} - \dot{x}_{\mathsf{L},\mathcal{I}}) + y_{\mathcal{I}}(v_{\mathcal{I}} - \dot{y}_{\mathsf{L},\mathcal{I}}) + z_{\mathcal{I}}(w_{\mathcal{I}} - \dot{z}_{\mathsf{L},\mathcal{I}})$$

v_{LOS}	scalar line-of-sight speed provided by lidar
$u_{\mathcal{I}}, v_{\mathcal{I}}, w_{\mathcal{I}}$	wind velocity at focal point in inertial coordinate system $\mathcal{I}$
$x_{\mathcal{I}}, y_{\mathcal{I}}, z_{\mathcal{I}}$	beam vector in inertial coordinate system $\mathcal{I}$
$\dot{x}_{\mathsf{L},\mathcal{I}}, \dot{y}_{\mathsf{L},\mathcal{I}}, \dot{z}_{\mathsf{L},\mathcal{I}}$	lidar system velocity measured by IMU in inertial coordinate system $\mathcal{I}$

Motion compensation

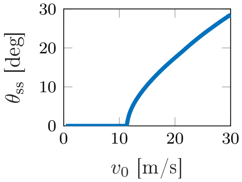
$$\begin{aligned} v_{\mathsf{LOS,mc}} &= v_{\mathsf{LOS}} + x_{\mathcal{I}}\dot{x}_{\mathsf{L},\mathcal{I}} + y_{\mathcal{I}}\dot{y}_{\mathsf{L},\mathcal{I}} + z_{\mathcal{I}}\dot{z}_{\mathsf{L},\mathcal{I}} \\ &= x_{\mathcal{I}}u_{\mathcal{I}} + y_{\mathcal{I}}v_{\mathcal{I}} + z_{\mathcal{I}}w_{\mathcal{I}} \end{aligned}$$

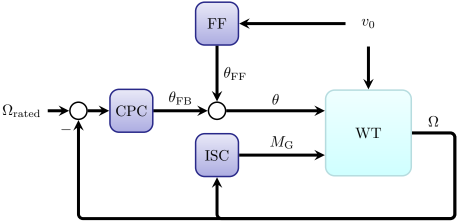
- beam vector from IMU‘s rotational DOFs and beam vector in lidar coordinate system $\mathcal{L}$
- $u_{\mathcal{I}}$ estimated by assuming $v_{\mathcal{I}} = w_{\mathcal{I}} = 0$, REWS via average over last full trajectory

Collective Pitch Feedforward Controller Design

$$J\dot{\Omega} = M_{\mathsf{a}}(\theta, \Omega, v_0) - M_{\mathsf{G}} \overset{!}{=} 0$$

$$\theta_{\mathsf{FF}} = \theta_{\mathsf{ss}}(v_0)$$





Control in full load operation for FOWTs

- pitch controller (CPC) maintains rated speed
- torque controller (ISC) applies constant torque

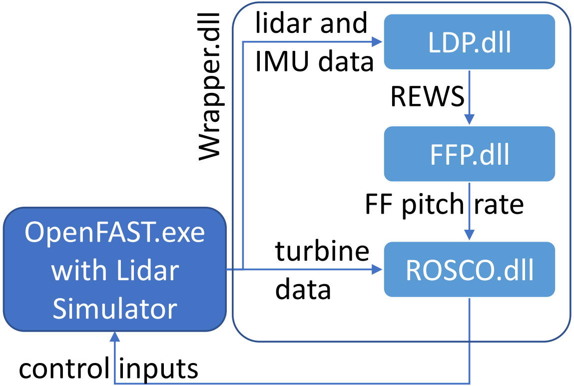
Collective pitch feedforward for onshore [5]

pitch follows static curve θ_{ss} to cancel out effects of changing wind speed v_0 in aerodynamics

Advantages

- simple update to conventional FB
- works over entire full load
- little model information
- guaranteed stability

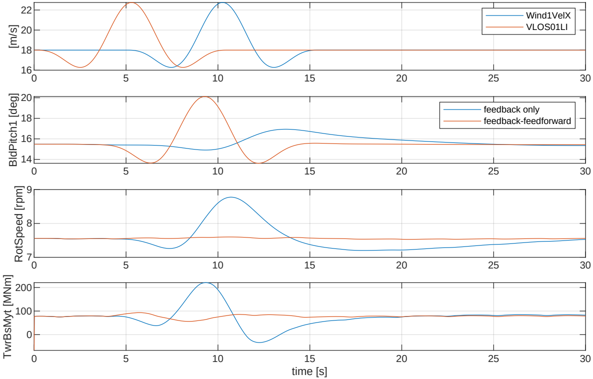
Communication Interface



Bladed Style Interface

- ROSCO: Reference Open-source controller [6]
- LDP: Lidar data processing
- FFP: Feedforward pitch
- Wrapper: calls other DLLs sequentially
- all DLLs have a parameter file

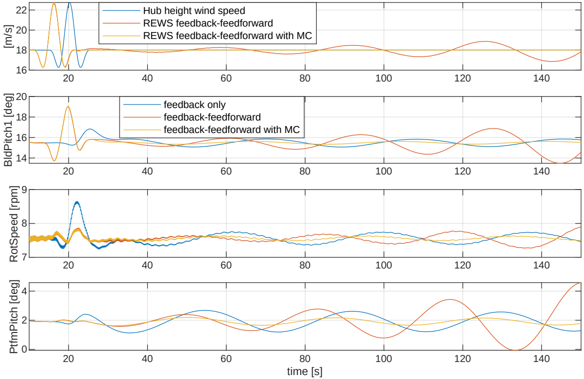
1/4: Perfect Preview on a Monopile Offshore Wind Turbine



extreme event on still water

- extreme operating gust at 18 m/s
- no waves
- full OpenFAST model
- almost no rotor and tower motions
- shows robustness with respect to model uncertainties

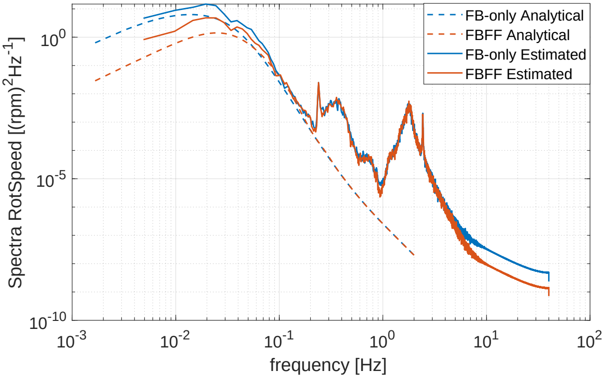
2/4: Perfect Preview on a Floating Offshore Wind Turbine



extreme event on still water

- full OpenFAST model with all platform motion DOF
- Motion Compensation (MC) of lidar measurement is important!
- LAC without MC is instable!
- reduces platform pitch amplitude by 63 % using LAC and MC

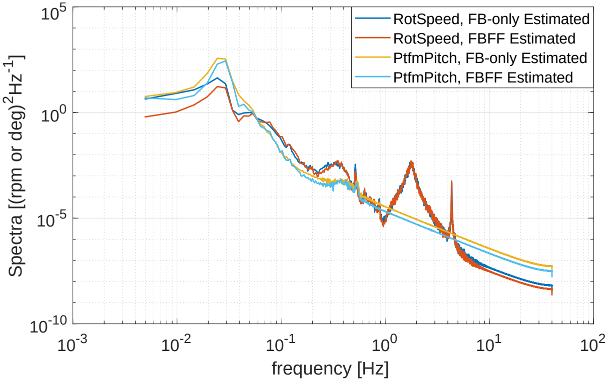
3/4: Realistic Preview on a Monopile Offshore Wind Turbine



turbulent wind on still water

- IEC class 1A at $18\,\mathrm{m/s}$, 6 seeds
- no waves
- full OpenFAST model
- commercial 4-Beam lidar measuring at $1D$
- feedforward reduces only low, correlated frequencies due to filter
- reasonable results: close to analytical spectra [7]

4/4: Realistic Preview on a Floating Offshore Wind Turbine



turbulent wind on still water

- IEC class 1A at $18\,\mathrm{m/s}$, 6 seeds
- no waves
- full OpenFAST model
- commercial 4-Beam lidar measuring at $1D$
- motion compensation is enabled
- additional notch filter at platform pitch eigenfrequency necessary
- rotor speed and platform pitch spectra is reduced at low frequencies

Conclusions

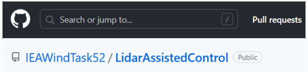
Objectives

- How can we integrate lidar signals into the controller of a floating wind turbine?
- How can you contribute to this exciting development?

A modular setup is very helpful!

- separating a complex task in small dedicated subtasks
- lidar data need to be motion-compensated with IMU data
- feedforward controller provides pitch rate to conventional feedback control

Just get started! Please let us know, if you need help!



- You can download, test and improve the tools! It's open source!
- You can participate in the LAC working group of IEA Wind Task 52!

Outlook: Current tasks under development in the IEA Wind Task 52

Next Steps

- add Python scripts additionally to Matlab scripts
- add other lidar systems
- improve lidar data processing including shear to avoid notch filter
- add other feedback controllers
- add full design load case 1.2 (normal operation)

References

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Please let me know if you have further questions!

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