

ENERGY

LIDAR Assisted Control and Hardware-in-the-Loop Testing using Bladed

Annual European Bladed User Conference 2016

Hamburg, Germany

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Light Detection And Ranging (LIDAR)

- Remote sensing technology similar to RADAR (**RA**dio **D**etection **A**nd **R**anging) and SONAR (**SO**und **N**avigation **A**nd **R**anging)
- Detection or navigation are referred to locating objects that could be in the air, space, underwater and underground
- Aim is to determine the distance or range of an object where time is crucial
- LIDAR uses light from a laser to image objects like aerosols

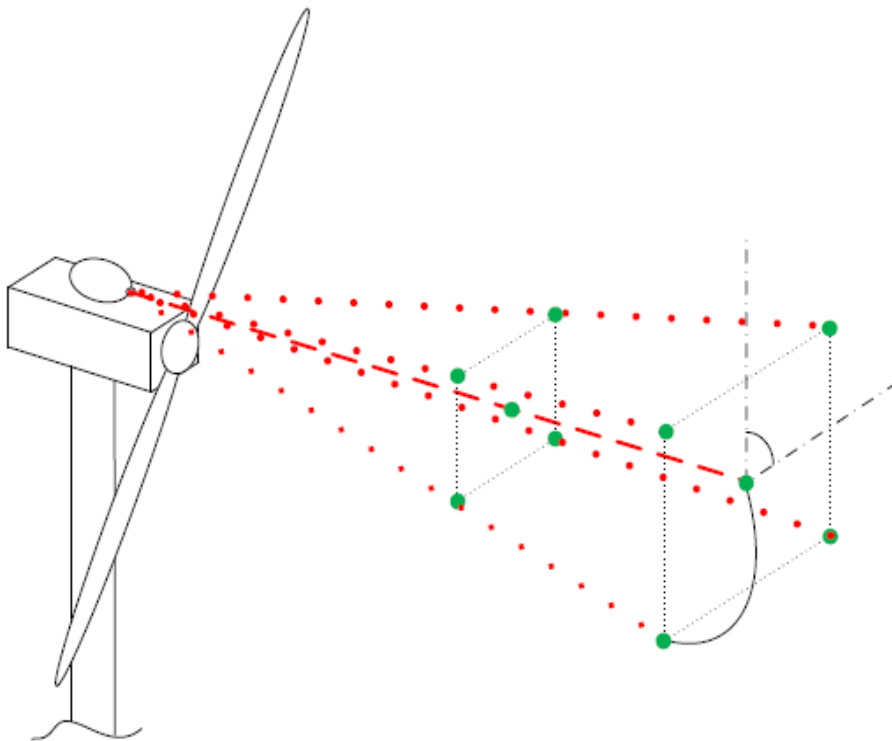
LIDAR types used in wind turbines

- Coherent or direct detection: these systems measure a Doppler shift information
- Achieved by comparing the frequency of the original and the backscattered light
- The Doppler frequency shift gives direct information of the wind speed component along the line-of-sight of the beam.
- Based on the waveform, LIDAR systems can be classified in pulsed or continuous wave
- The estimated wind speed is very useful information to the wind turbine controller

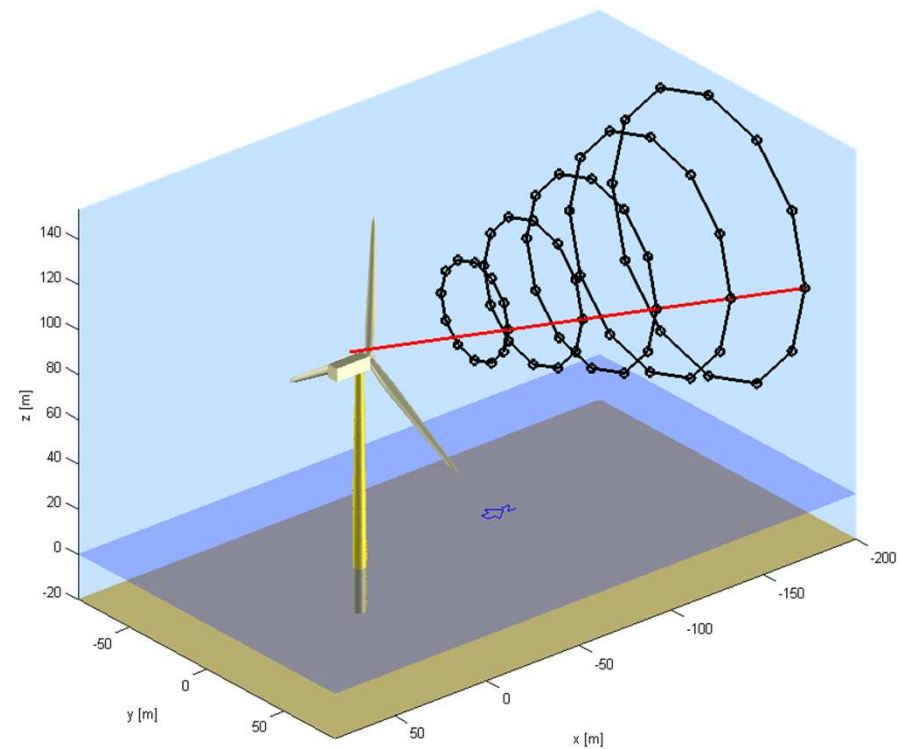
Turbine mounted LIDAR

- Laser Doppler anemometer: Laser beam projected forward from turbine provides advance information about the approaching wind field

Pulsed LIDAR



Continuous Wave LIDAR

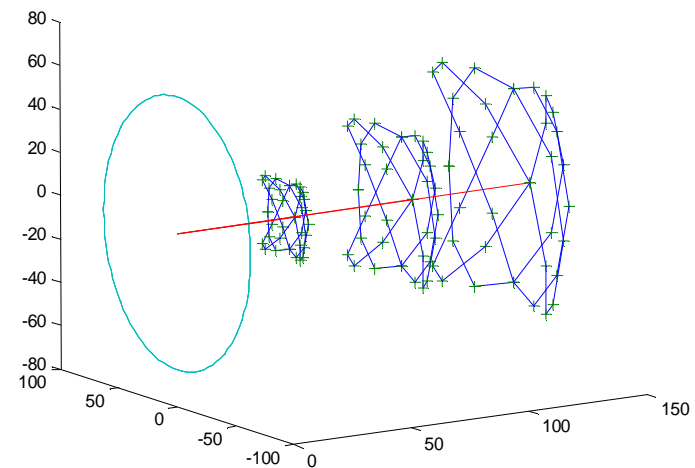
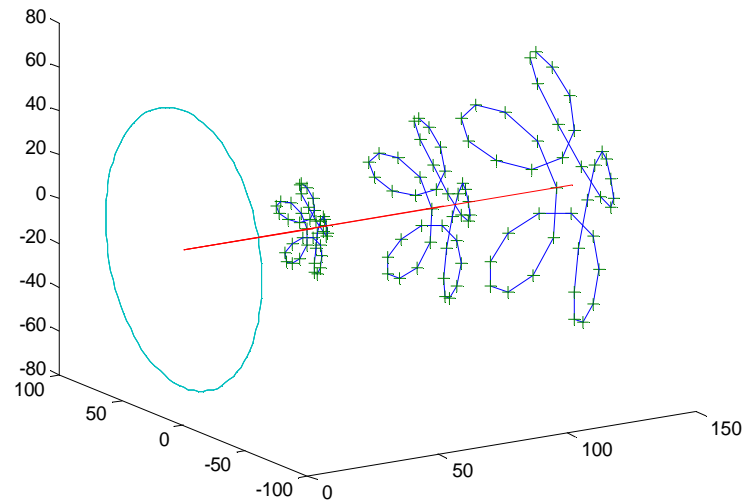
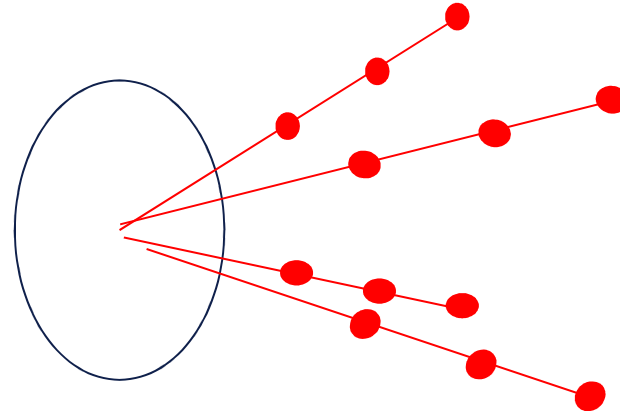


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Turbine mounted LIDAR

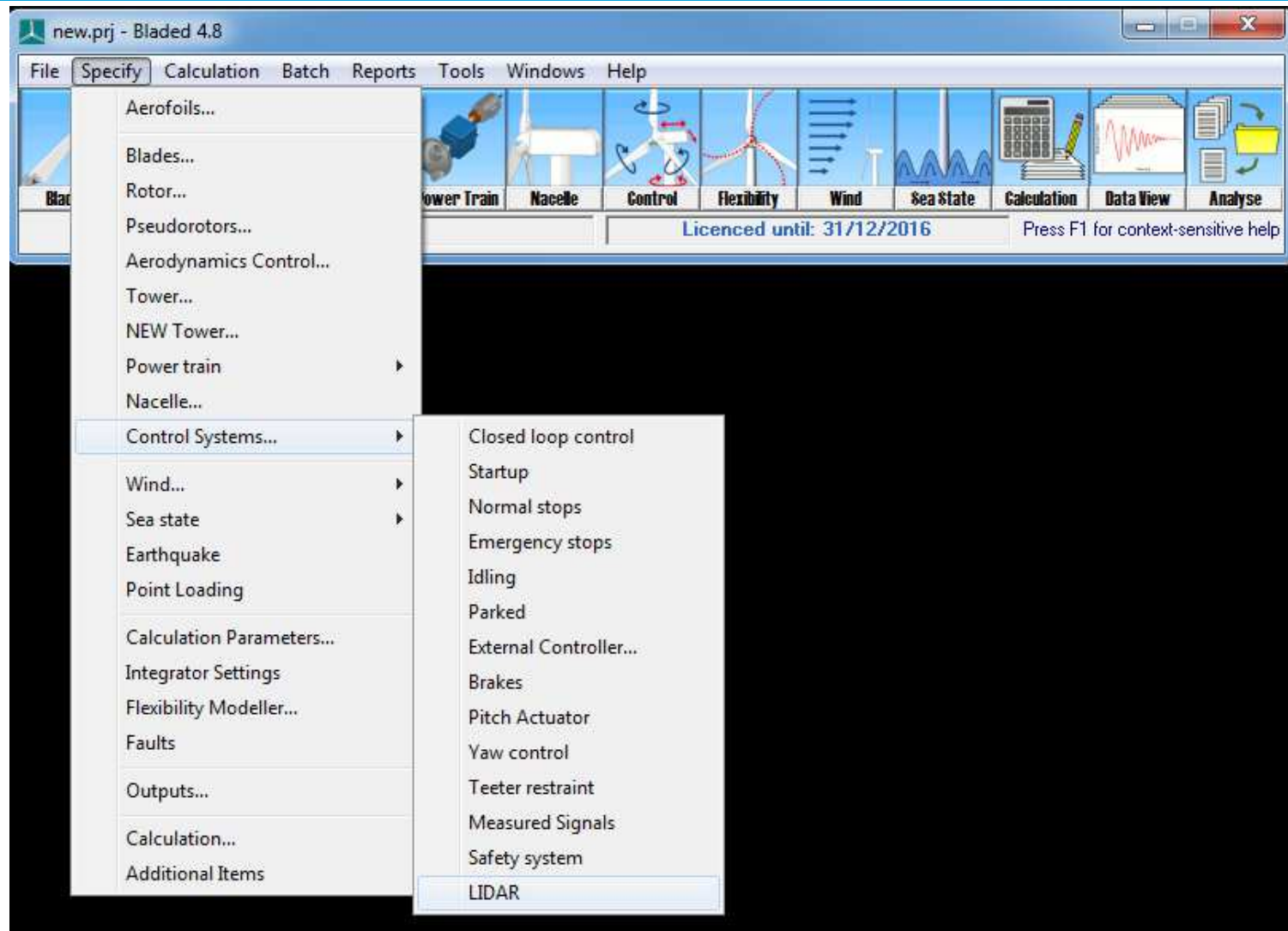
Scanning patterns:

- Scanning or multiple fixed beams
- Single or multiple distances
- Different figures as scanning patterns



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LIDAR modelling in Bladed



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LIDAR modelling in Bladed

LIDAR

☒ Enable LIDAR

Weighting Function

LIDAR Type: Pulsed / General

Weighting Function: 81 value(s)

LIDAR Range

Use external controller to set focal distance: ☐

Focal Distance(s): 1 items Edit List

1 160 m

LIDAR Beam Angles

Use external controller to set beam angle: ☐

Scan Mode: Circular Scan

Angle to Centreline: 14.99999999999998 deg

LIDAR samples per complete scan: 50

Sampling Rate

Use external controller to command LIDAR: ☐

Interval between successive measurements: 0.02 s

Time for a complete scan: 1 s

Weighting Function

Weighting function for measured velocities to simulate focal error

LIDAR Beams **Weighting Function**

Distance from focal point (-)	Weighting (-)
-25	0.0386
-24	0.0418
-23	0.0454
-22	0.0494
-21	0.054
-20	0.0593
-19	0.0654
-18	0.0724
-17	0.0806
-16	0.0902
-15	0.102
-14	0.115

Add Row Remove Row(s)

Weighting (-)

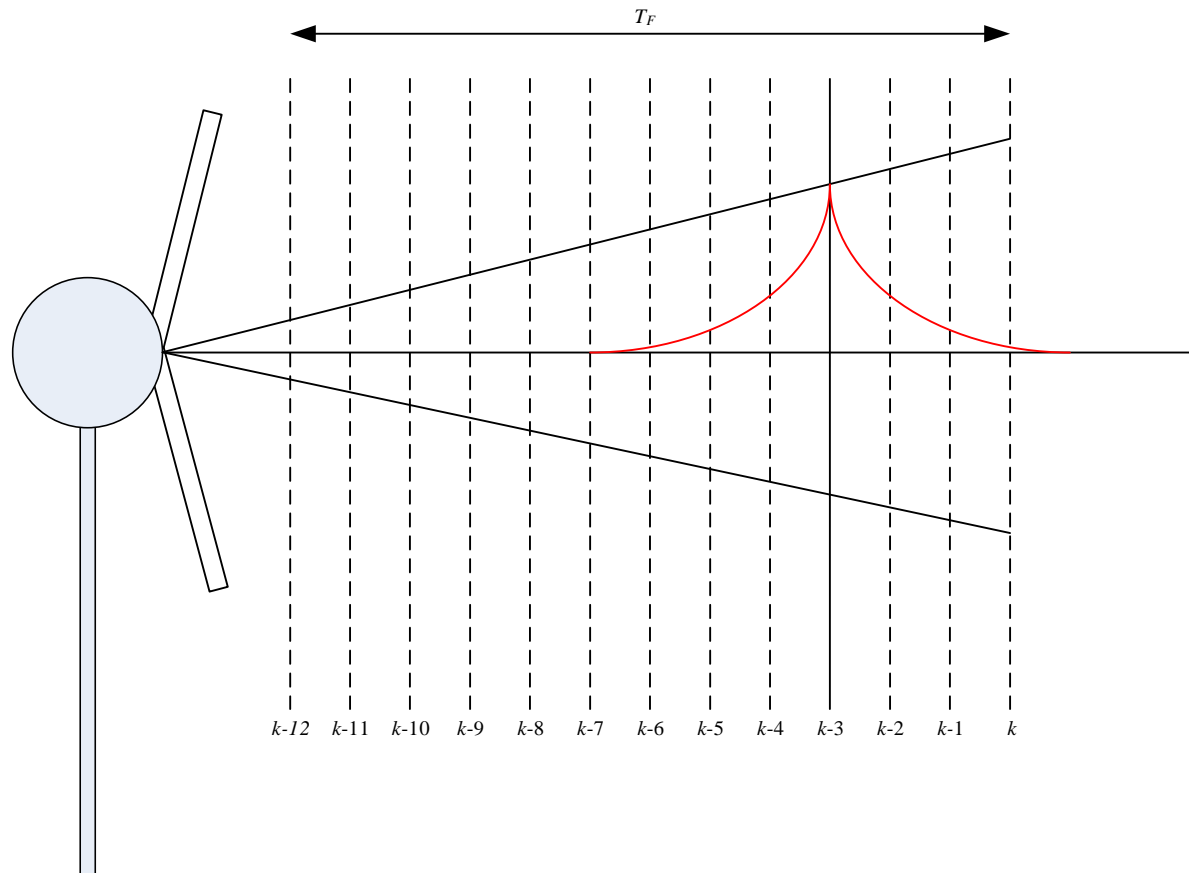
Distance from focal point (-)

OK Cancel

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LIDAR modelling in Bladed

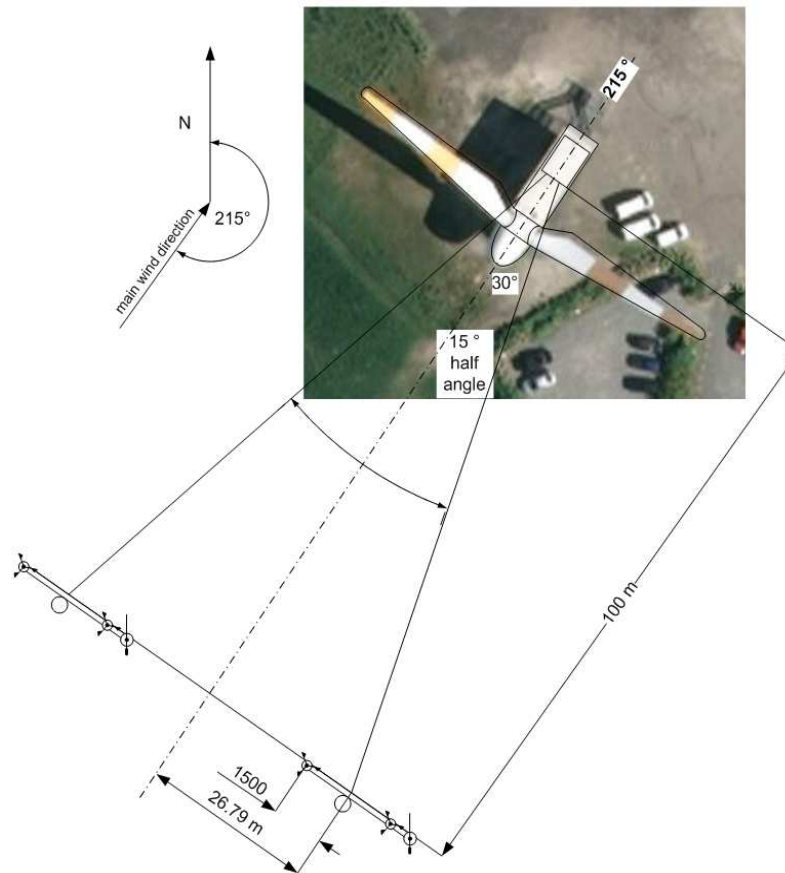
The weighting function combines measurements of the wind speed at a range of distances along the beam line to calculate the returned wind speed.



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LIDAR modelling in Bladed

LIDAR Beams		Weighting Function							
Insert New Row		Delete Selected Rows							
Mounting	Blade Number	Rotor Number	Blade Station	X (m)	Y (m)	Z (m)	Azimuthal Angle about Centreline (deg)	Angle to Centreline (deg)	
Nacelle	0	0	0	4.5	0	5	0	0	



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LIDAR modelling in Bladed

Wind

Upwind turbine wake Define turbulence Annual wind distribution

Time varying wind Wind shear Tower shadow

☐ No Variation
☐ Single Point History
☒ 3D Turbulent Wind
☐ Transients
☐ Refer wind speed to hub height
 View Wind Data

☐ Frozen turbulence ☒ Evolving turbulence

Turbulent wind file name: ... Properties...
 Additional wind file name: ... Properties...
 Mean wind speed: m/s 0
 Height at which speed is defined: m 0
 Turbulence Intensity (longitudinal): % 0
 Turbulence Intensity (lateral): % 0
 Turbulence Intensity (vertical): % 0
 Wind direction (from north): deg 0
 Flow inclination: deg 0

Additional sinusoidal wind direction transient
 Amplitude of direction change: deg 0
 Start time for transient: s 0
 Duration of transient: s 0
 Type of transient (half/full wave): Full

Continuous direction change
 Rate of direction change: deg/s 0

Set wind file defaults
 Set IEC turbulence
☐ Allow wind file to wrap around
 Height of turbulent wind field
☐ Centred on hub height
☒ Best fit for rotor and tower
 Interpolation scheme:
 Fully Cubic
☒ Cubic interpolation for LIDAR measurement
 Apply Reset

OK Cancel

Bossanyi, E.A. "Un-freezing the turbulence: improved wind field modelling for investigating Lidar-assisted wind turbine control," in Proceedings of the European Wind Energy Copenhagen, Denmark, 2012.

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LIDAR modelling in Bladed

Measured Signals

Random Number Seed

0

Turn Off All Noise?

☐

Log Signals?

☐

Fixed Hub Fz

Pitch Angle

Pitch Rate

Pitch Actuator Torque

Pitching Inertia

Pitch Bearing Friction

Pitch Bearing Stiction

Blade Out Of Plane Bending Moment

Blade In Plane Bending Moment

Pitch Bearing Mx

Pitch Bearing My

Pitch Bearing Mz

Pitch Bearing Radial Force

Pitch Bearing Axial Force

Pitch Bearing Fx

Pitch Bearing Fy

Blade Station Wind Speed

Blade Station Angle Of Attack

Aileron Angle

Aileron Rate

Blade Station Position X

Blade Station Position Y

Blade Station Position Z

Blade Station Position X Rotation

Blade Station Position Y Rotation

Blade Station Position Z Rotation

Lidar Beam Focal Point Velocity

Quality

Signal Quality

As Measured

Signal Noise Properties

Noise Type

Uniform (Rectangular)

Noise Magnitude

0 m/s

Discretisation

Sampling Period

0 s

Discretisation Step

0 m/s

Transducer Properties

Lag Type

2nd order

Transducer Faults

Lag Type

Defines the dynamics of the transducer's response to the inputted simulated value.

Parameters

Frequency (f)

1.0000000000000007 Hz

Damping factor (ζ)

0.8 -

$$\frac{d^2x(t)}{dt} + 2\zeta\omega \frac{dx(t)}{dt} + \omega^2 x(t) = \omega^2 u(t)$$

$u(t)$

 = Input

$x(t)$

 = Output

ω

 = Frequency (rad/s) = $2\pi f$

ζ

 = Damping factor

1

0

0.4

0.8

1.2

1.6

Time (s)

Input

Output

Encrypt

Decrypt

OK

Cancel

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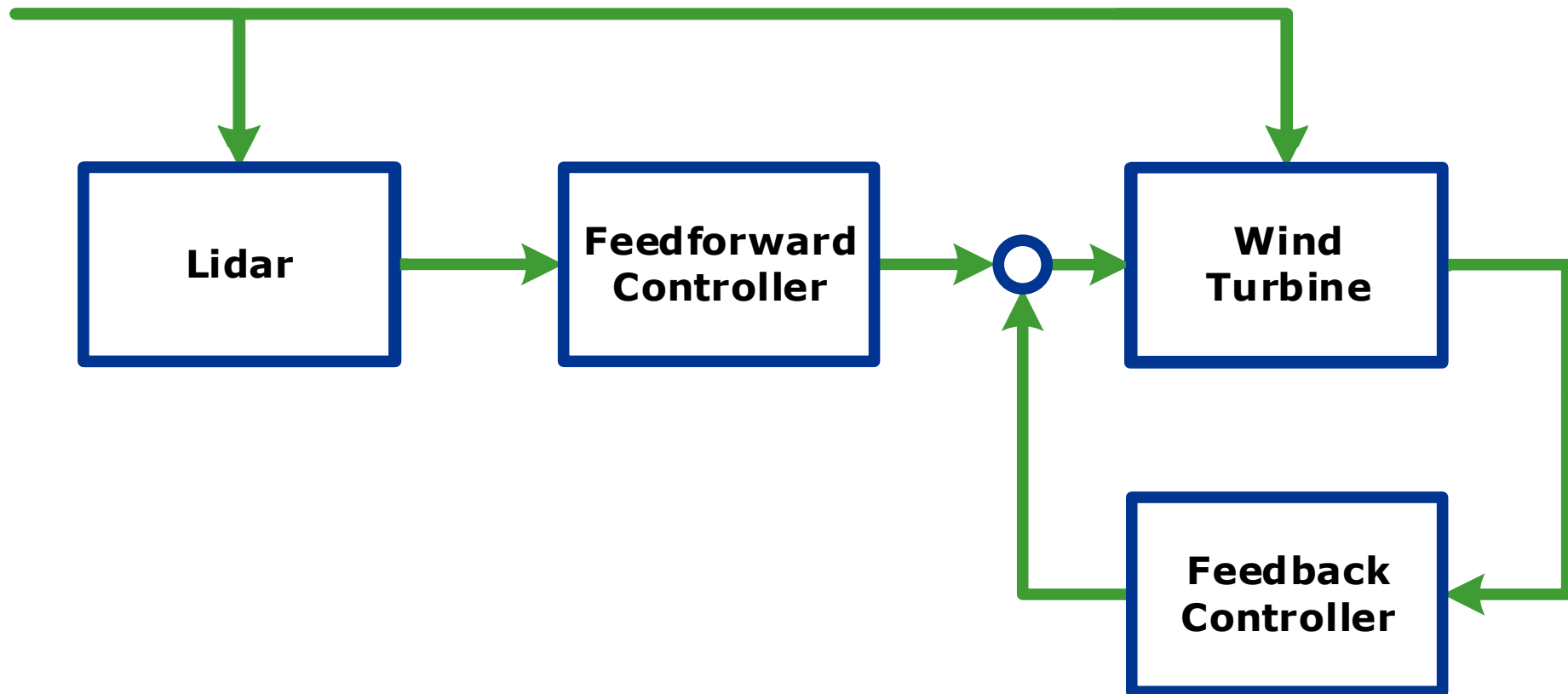
LIDAR modelling capabilities in Bladed: Summary

- Different LIDAR configurations can be simulated
- A LIDAR beam can be emitted from a point fixed to the nacelle or the spinner or the blade.
- Continuous wave or pulsed beams can be modelled
- Multiple beams can be modelled: for example a number of beams pointing in different directions and radial stations
- Simultaneous measurements are possible at multiple focus distances (ranges).
- Scanning or steering of the LIDAR beam(s), and/or changes to the focus distance(s) and timing of samples can be defined by the external controller
- The wind velocity relative to the LIDAR is sampled along the beam line, taking into account any velocities of the LIDAR itself due to motion or structural vibration of the part of the turbine to which it is mounted.
- Around each focus point, the wind velocity is sampled at a number of points along the beam line.
- A weighting function is used for averaging the line-of-sight velocities

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LIDAR Assisted Control

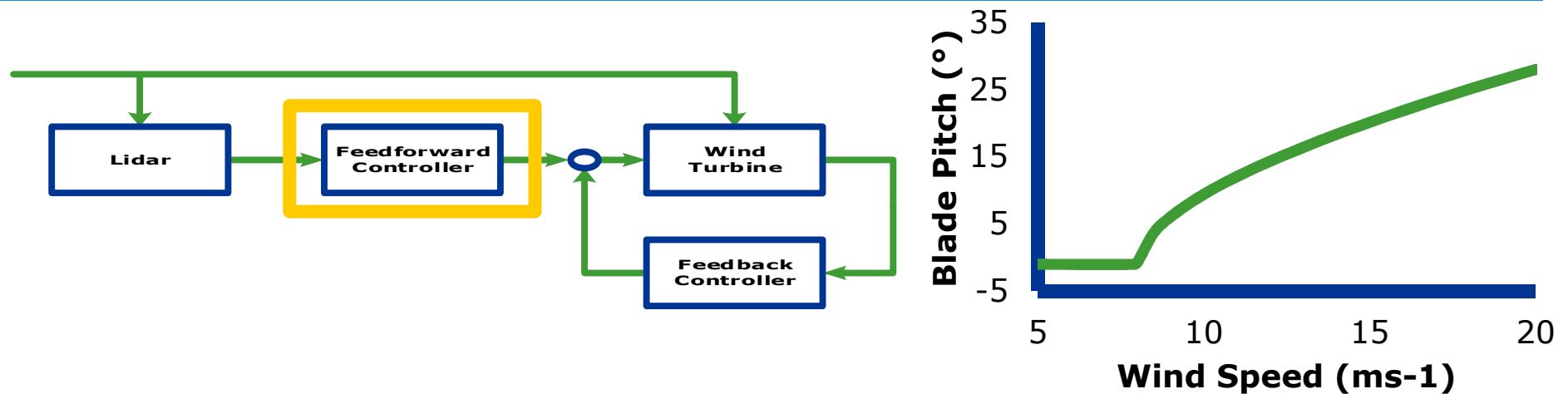
Wind field



Bossanyi, E. A. Kumar, A. and Hugues-Salas, O. "Wind turbine control applications of turbine-mounted LIDAR"
Journal of Physics: Conference Series 555 (2014) 012011

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Lidar Assisted Control



$$\dot{\theta}_{FF}(t) = \frac{\hat{\theta}_{ss}(V(t + \tau)) - \hat{\theta}_{ss}(V(t))}{\tau}$$

Feedforward method:

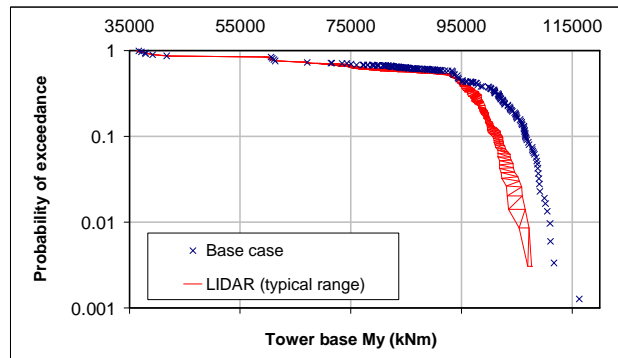
- Take future estimated wind speed from LIDAR and look up for future steady-state pitch angle
- Add pitch rate obtained from the difference between present and future pitch

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LIDAR Feedforward: Simulation results

NREL 5MW baseline

- 14% tower base lifetime fatigue load reduction
- 8% reduction in tower base extreme

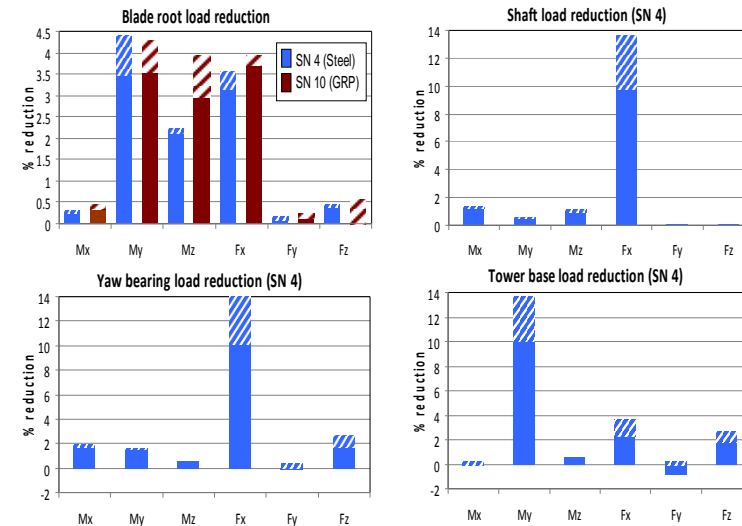


FORCE 7MW baseline *

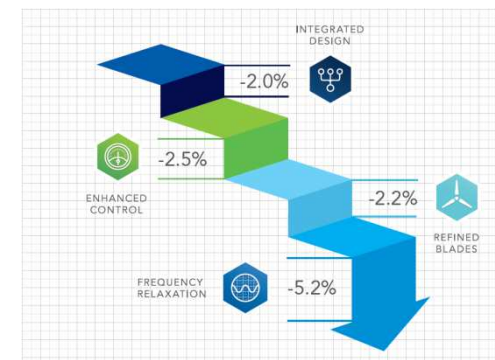
- 7% lifetime fatigue load reduction in tower base bending moment with Feed Forward Control
- Model Predictive Control (MPC) improves this to 11%

* Dobbin, J. et. al., "Fully Integrated Design: Lifetime Cost of Energy Reduction for Offshore Wind" Proceedings of the Twenty-fourth, International Ocean and Polar Engineering Conference, 2014, vol. 3, pp. 415–423.

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FORCE 7MW LCoE % reductions



Field test results at NREL with five-beam LIDAR

- A field-testing campaign to test LIDAR Assisted Control (LAC) has been undertaken on a 600-kW turbine using a fixed, five-beam LIDAR system.
- The campaign compared the performance of a baseline controller to four LACs with progressively lower levels of feedback using 35 hours of collected data.



Photo Credit: Lee Jay Fingersh, NREL 33621

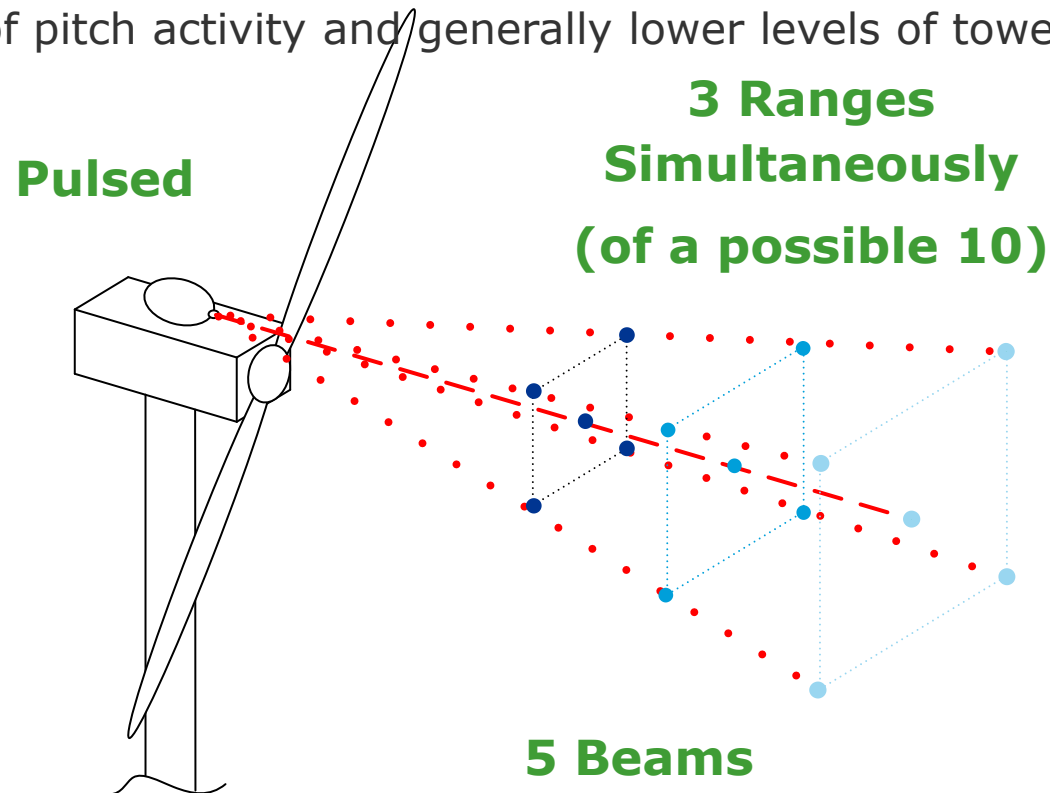
Kumar et al. "Field testing of LIDAR assisted feedforward control algorithms for improved speed control and fatigue load reduction on a 600kW wind turbine", EWEA Paris, France, November 2015.

Bossanyi, EA et al., "Wind turbine control applications of turbine-mounted LIDAR," Proc. Torque From Wind conference, Oldenburg, Germany, 2012.

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Field test results at NREL with five-beam LIDAR

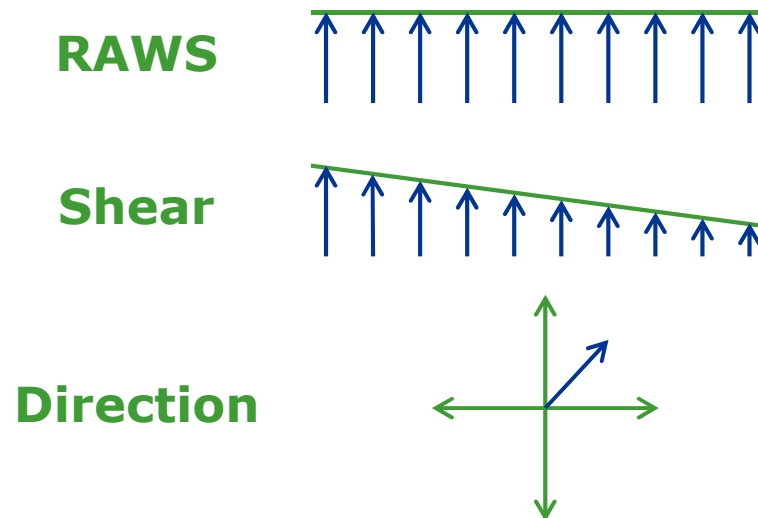
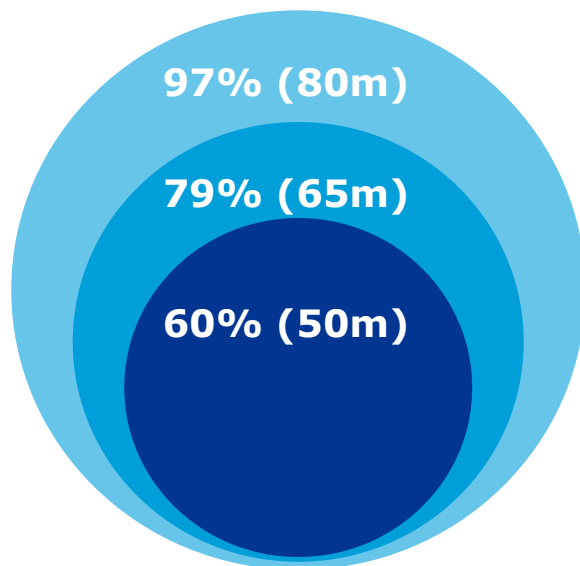
- Collected data shows that utilising measurements from multiple range gates on a pulsed LIDAR system can result in rotor averaged wind speed (RAWS) estimates with greater levels of correlation with wind speed at the rotor than using a single range gate.
- The LACs showed higher levels of speed control performance with significantly reduced levels of pitch activity and generally lower levels of tower excitation.



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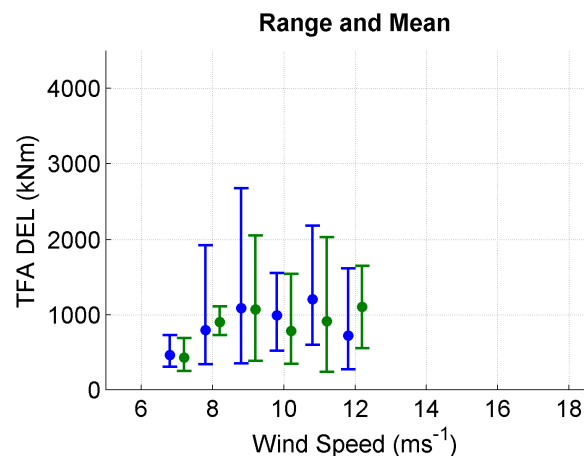
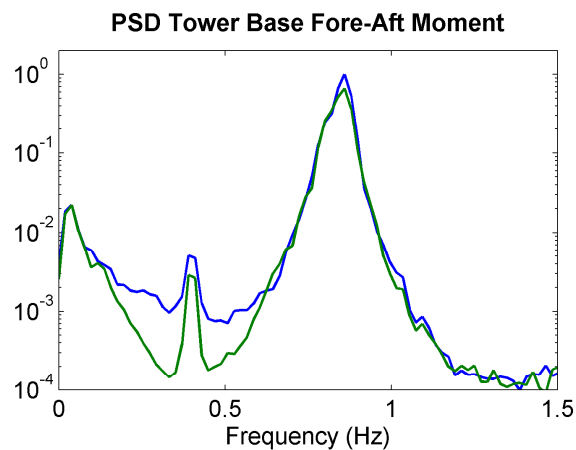
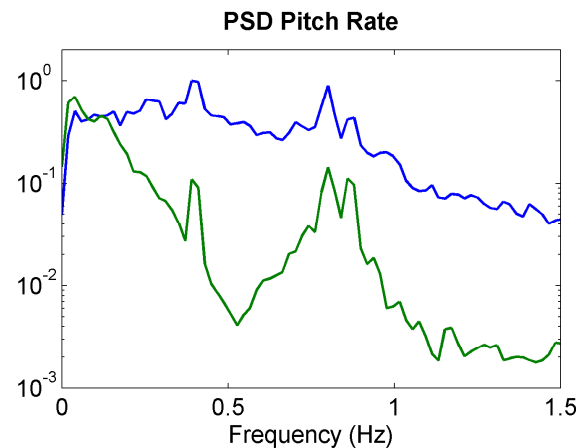
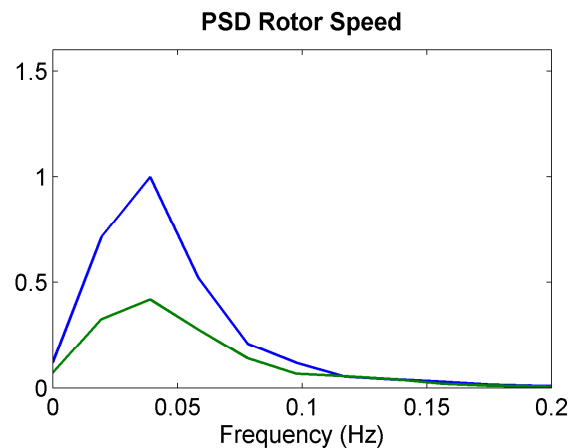
Field test results at NREL with five-beam LIDAR

- The feedforward control algorithm makes use of the RAWS data from three range gates focused at 50, 65 and 80m.
- These gates correspond to covering the centre and approximately 63%-100% of the rotor radius using a beam angle of 15° from horizontal.
- The LIDAR processes the line-of-sight data to return the current RAWS, wind shear and wind direction estimate for each range gate.



Field test results: 38% Controller Gain

Test with (green) and without (blue) Lidar assisted control with full pitch-speed controller gain



Speed control improvement
Further reduction in pitching
above 0.2Hz
Further reductions in tower
spectral response/DEL, 1P

- LAC easily added to existing controllers
 - Relatively low levels of tuning for immediate performance increase
 - No impact on stability
- LAC achieved better speed regulation than feedback only
- Detuning resulted in:
 - Reduced pitch activity
 - Reduced tower spectral response
 - Reduced tower fatigue

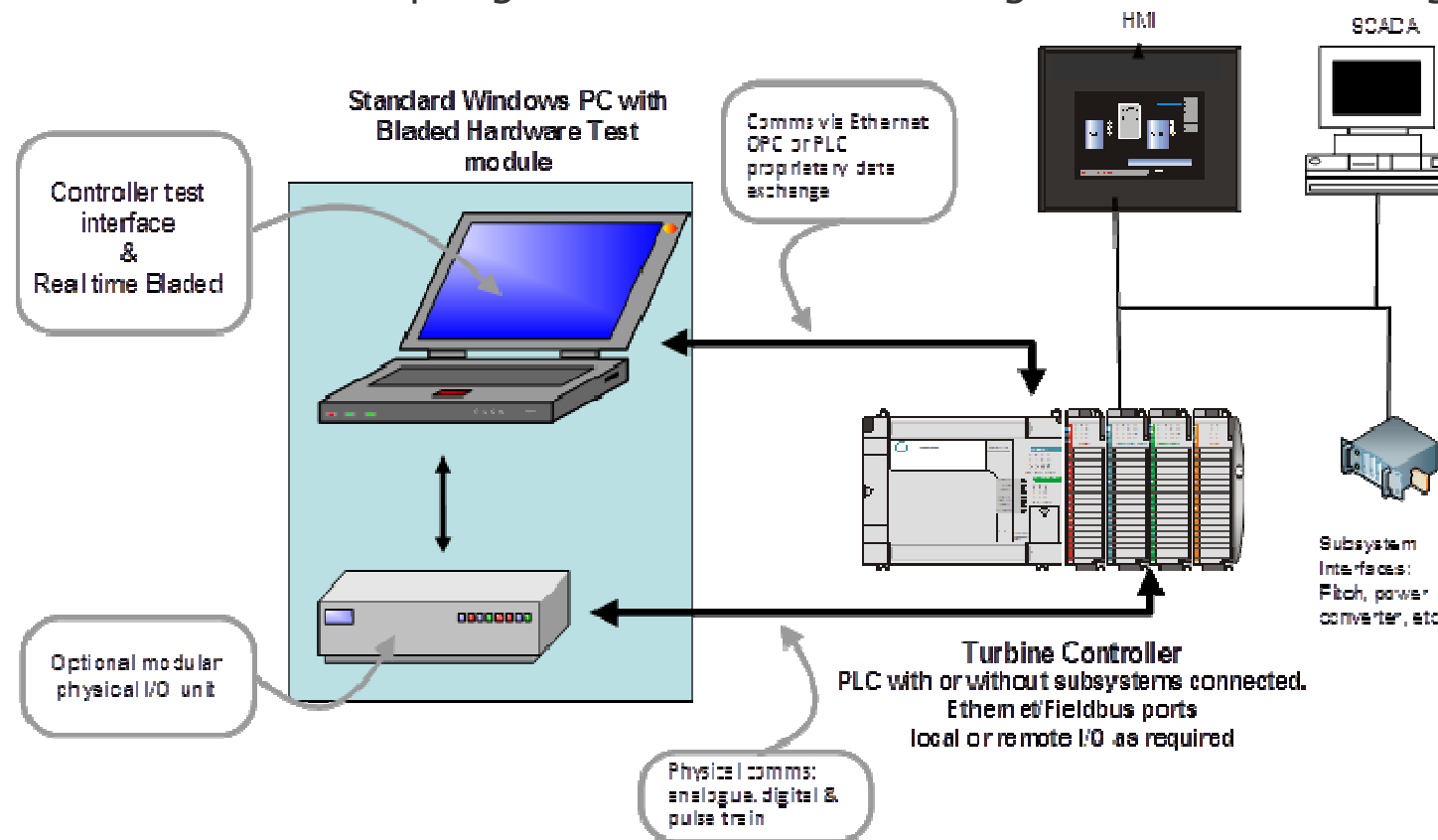
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Bladed Hardware Test Module

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Bladed Hardware Test Module (BHTM)

- Connects several devices (software or hardware) together and pass information between those devices
- Defines test procedures composed by sequential instructions
- Contains a .NET C# scripting environment for coding in hand-written logic



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Bladed Hardware Test Module (BHTM)

- Transforms the Bladed design simulation to a real-time hardware-in-the-loop simulation
- Use the same turbine model developed in turbine design and load calculations
- Customise the Bladed simulation to model complex behaviour
- Flexibly connect turbine hardware to the simulation
- Versatile set of input/output modules easily added to the simulation
- Test scripting system to manipulate the simulated environment and evaluate pass/fail results
- Hardware in the loop tests can reduce the risk of failures, delays and expensive rework in commissioning and actual turbine use, can improve confidence in the turbine product and could help with procurement decisions.

Thank you!

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