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Review of LIDAR-assisted Control for Offshore Wind Turbine Applications

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Abstract

Nacelle-mounted, forward-facing Light Detection and Ranging (LIDAR) technology is able to provide knowledge of the incoming wind so that wind turbines can prepare in advance, through feedforward control. LIDAR can aid in improving wind turbine performance across the full operating range, assisting with torque control in below rated wind speeds, pitch control in above rated wind speeds and yaw control for correctly aligning the turbine rotor with the incoming wind direction. The motivations are for decreasing structural loads, resulting in reduced maintenance and extended lifetimes of turbines and their components, and increasing power capture, both of which can lead to reductions in the levelised cost of energy. This paper provides a review of control strategies that have been employed for LIDAR-assisted turbine control. This paper reviews the computational and practical studies that have been performed for both bottom-fixed and floating turbines and the journey that the field has undertaken since its conceptualisation. Detail is provided of the key differences between fixed and floating offshore turbine dynamics. The paper concludes with guidance for future work within the field, with a focus on floating turbines, as the extent of the literature is scarce when compared to bottom-fixed. Suggestions are offered for how the future studies can better account for the current and future industry landscape. Opportunities for testing of LIDAR-assisted floating turbine control in the field, its benefits for floating substructure design, and the steps needed to be taken to ensure its increased utilisation on industrial projects are also discussed.

1 Introduction

Offshore wind turbines are subject to cyclic stresses and disturbances from wind and wave loading. These can cause wear and damage to the turbines components, leading to failures, downtime, and corrective maintenance. The occurrence of such events contributes to operations and maintenance expenditure (OPEX), which accounts for around 30% of the lifetime costs of a bottom-fixed offshore wind farm [1]. The OPEX of a floating wind farm is likely to be even greater due to their (typically) greater distance from shore and the challenges in accessing the turbines due to the harsher environments in which they are situated. Therefore, practical solutions capable of reducing turbine loads and, consequently, structural damage, component failure rates, downtime, and OPEX are highly desirable as they can contribute to reducing the lifetime costs of an offshore wind farm.

Nacelle-mounted, forward-facing Light Detection and Ranging (LIDAR) technology can provide knowledge of the incoming wind field, which can allow for superior wind turbine control, as the incoming disturbance can be anticipated and the turbine can be prepared accordingly. This has the potential to reduce the levelised cost of wind energy, by reducing structural loads to extend maintenance intervals and the lifetime of wind turbines, as well as to increase power capture.

Traditionally, turbines utilise feedback (FB) torque, pitch and yaw control. Feedback control feeds back the turbine's outputs to be used as inputs to the relevant controller, which, for wind turbines, is dependent on the wind conditions. In below rated wind speeds, torque control is used to adjust the rotor speed to maintain the optimal tip speed ratio, through control of the generator torque. In above rated wind speeds, blade pitch control is utilised to maintain the rotor speed at its rated speed. Yaw control is undertaken to ensure that the nacelle of the wind turbine is correctly aligned with the wind.

The pitfall of feedback control is that the turbine is reacting to the wind once it has already impacted upon it. LIDAR-assisted control can overcome this through inclusion of a feedforward control loop (in combination with the feedback control loop), where the incoming disturbance (the wind speed) is measured in advance of it impacting upon the turbine. Knowledge of the incoming disturbance is then used to formulate control commands that can be used by the turbine to pre-emptively prepare for the disturbance.

This study will review the research that has been undertaken within the field of LIDAR-assisted control for both bottom-fixed and floating offshore wind turbine configurations. Studies have investigated the capability of LIDAR-assisted control for improving turbine performance and reducing loads through implementation of feedforward-feedback (FF-FB) torque, pitch and yaw

control.

The paper will begin with a summary of the key background topics (Section 2), followed by an outline of the methodologies utilised in completing this review (Section 3). Section 4 will detail the results of the literature review, including assessment of previous research into LIDAR-assisted control of bottom-fixed and floating turbines. Subsection 4.1 presents a summary table of the reviewed studies, to provide a simple breakdown of the key findings within the literature. Section 5 details the key future research opportunities that have been identified, covering design, control and commercial aspects. The focus of Section 5 will mainly be on floating turbines as the extent of the literature is relatively scarce when compared to bottom-fixed wind. Finally, Section 6 will present the conclusions of the study.

2   Background

This section will cover the background topics applicable to both bottom-fixed and floating turbines, including LIDAR's mode of operation, traditional turbine operation, and the modifications to this that are characteristic of LIDAR-assisted control. Although the overarching concept is the same for floating wind applications, the adjustments that need to made to accommodate for the floating dynamics will also be detailed.

2.1   LIDAR

LIDAR operates by firing high-speed laser pulses, which are reflected by particulates in the air. The sensor can then measure the time taken for the pulses to return. The sent and reflected wavelengths are compared and the Doppler effect is used to determine the wind speed [2].

There are two main LIDAR configurations, continuous-wave and pulsed, shown in Figure 1. Continuous-wave (CW) LIDAR uses a beam that is focused at the desired distance ahead of the LIDAR, termed the focal distance. CW LIDAR is only capable of recording time-series measurements at the specified focal distance. Pulsed LIDAR is configured to multiple different focal distances along a range of rotor diameters (RD) away from the turbine. Multiple measurements can be taken at each focal distance by the pulsed LIDAR. The time series at different ranges can be time shifted and combined to give one wind speed [3].
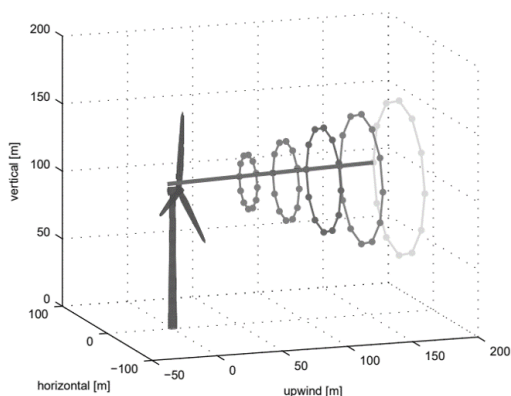

Figure 1: Continuous-wave (line) and Pulsed (circles) LIDAR configurations, from [4].

2.2   Turbine operation

Most modern industrial wind turbines operate at variable rotor speed, through adjustment of the torque of the generator and by using collective blade pitch control. As wind turbines with large rotors experience asymmetric loading on the blades due to wind speed variations across the rotor swept area, the concept of individual pitch control has also been explored [5][6].

2.2.1   Operating regions

Turbines are typically categorised into 3 operating regions [7][8]:

- Region 1, when the wind speed is below the cut-in speed of the turbine and it does not operate.

- Region 2, between cut-in and rated wind speed, when the rotor speed is varied through generator torque control and with a fixed blade pitch, to maximise the rotor efficiency.

- Region 3, when the wind speed is above rated, but below the cut-out speed. In this region, there is more power in the wind than the turbine is rated to capture. Therefore, generator torque is fixed and blade pitch control is used to shed power to maintain the rotor at its rated speed. As wind speed increases, the pitch angle increases. An increase in the pitch angle will increase the angle of attack, causing both the lift and drag forces to increase, resulting in the rotor speed decreasing.
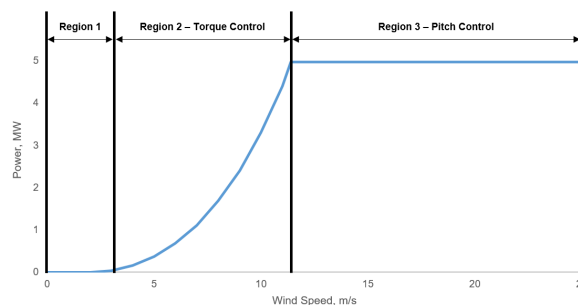

Figure 2: Typical power curve of a 5 MW turbine, from [8], Indicating the key operating regions and their control modes.

There also exists a transition region termed Region 2.5, where the rotor speed reaches its rated value before the generator torque reaches its rated value [8]. When the wind speed is above the cut-out speed, the turbine does not operate, in order to protect it from extreme loads and damage.

2.2.2   Turbine control

In terms of controller design, typically, wind turbines are controlled using feedback control through Proportional-Integral (PI) controllers. In both torque and pitch control, the generator speed is used as the feedback input because the wind speed varies across the rotor [8]. Explanations for the mode of action of torque and pitch control can be found in [7]. The pitfall of feedback only control is that the turbine is reacting to the wind once it has already impacted upon it. LIDAR technology presents the opportunity to measure the wind before it reaches and

impacts upon the turbine, to anticipate the control inputs required to reject the disturbance.

To achieve maximum power capture, turbine rotors must also be aligned with the wind direction, as misalignment can result in loss of power capture [9][10]. Alignment is achieved through yaw control and traditionally uses a nacelle mounted wind vane to detect the wind direction. However, measurements from these devices are erroneous due to the interference effect from the wake of the rotor blades [11]. Another disadvantage is that the wind vane sensors can only measure at a single point and so cannot detect variations across the rotor swept area [12]. However, nacelle-mounted LIDAR is able to overcome these shortcomings (and biases in the measurements that result) by measuring the incoming wind speed across the rotor disk.

2.3   Turbine control with LIDAR

Implementing LIDAR measurements into wind turbine control typically entails the inclusion of a feedforward control loop, in combination with the existing feedback control. An example block diagram for LIDAR-based FF-FB pitch control is given in Figure 3 [7].
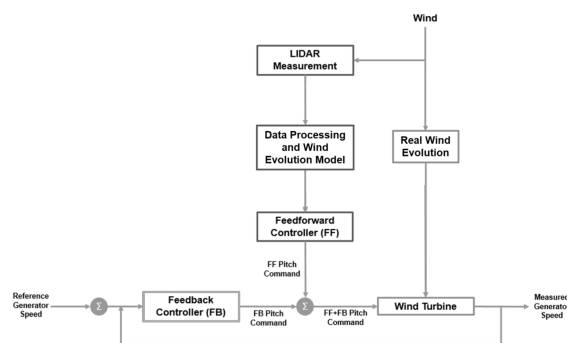

Figure 3: LIDAR based feedforward controller, adapted from [7]. The dark grey blocks denote the additional blocks required for the feedforward control, which adds to the existing feedback control.

As shown in Figure 3 the feedforward control loop addition consists of three parts:

- LIDAR measurement, where the LIDAR measures the incoming wind at the desired location ahead of the turbine.

- Data processing and wind evolution model, which accounts for measurement error and predicts how the wind field will evolve in the space between the point of measurement and the rotor, to ensure coherence between the measured and actual wind speed.

- The feedforward controller, which converts the wind speed measurement into a pitch command, that is added to the pitch command from the feedback controller.

The prospect of using LIDAR for assisting bottom-fixed turbine control was first explored by Harris et al. [13]. In their computational study, they investigated the potential of using LIDAR for load mitigation in Region 3 (pitch control) and found that damage equivalent flap loads could be reduced by approximately 10% under turbulent wind conditions. Harris et al. [13] identified key research areas, which paved the way for future studies into LIDAR-assisted control. These included modelling studies of the other turbine regions and of larger, commercial-scale turbines as well as performing field testing to validate the numerical models.

2.4   Bottom-Fixed vs. Floating turbine dynamics

The dynamics of floating turbines are inherently different to those of fixed turbines, due to the different natural frequencies imposed by the floating substructures. This section will outline the key implications of the differences in fixed and floating turbines for controller design, and how nacelle-mounted LIDAR can be a useful tool in overcoming them.

A study by Jonkman and Matha [14] modelled 3 types of floating offshore wind platforms (Tension Leg Platform (TLP), Spar and Barge) and compared them to an onshore turbine. All of the floating turbines showed increased loads on turbine components when compared to the onshore turbine [14]. It has also been noted that platform motions render a floating system's behaviour more dynamic than their fixed-bottom counterparts, introducing higher demands on the control system [15]. Therefore, new blade pitch control concepts capable of regulating the rotor speed and reducing structural loads in the presence of a low-frequency pitch motion of a floating platform have been recommended [15].

A commonly reported issue for floating turbines is that the pitch controller can become unstable in above rated wind speeds [16][17][18]. This is because the turbines are subject to softer foundation properties, leading to lower natural frequencies and unfavourable coupling between platform motion and pitch control [16][18]. The floating platform rigid-body modes of oscillation will tend to have a natural frequency that is an order of magnitude lower than the tower modes of vibration frequencies, linked to the structural elasticity of the tower, and within the bandwidth of the pitch controller [17]. The primary issue is that, when using controllers designed for bottom-fixed turbines, the floating turbine's pitch controller will adjust pitch angles during the turbine's motion, reducing the thrust when the motion is towards the wind and increasing the thrust when the motion is away from the wind [16]. When the blade pitch control actuation frequency is similar to the floating platform rigid-body pitch oscillation natural frequency, negative damping (oscillations increasing) can occur [16].

Methods have been proposed to overcome these instabilities. Larsen and Hanson [16] used simulations to demonstrate the effectiveness of changing the control objective in Region 3 from constant generator power to constant generator torque. This was to minimise drive train loads in general, but also to provide the possibility for reducing the pitch activity [16]. Fleming et al. [17] reviewed three control modifications for floating wind turbines. These were Detuning, Scheduled-Detuning and Detuning+Nacelle Feedback. Detuning is the method of detuning the pitch controller such that its bandwidth doesn't include the surge mode of the platform and was enacted by adjusting filter parameters and PI gains to reduce their bandwidths [17]. It was found that this method incurred a trade-off where greater amounts of detuning led to superior stability at the expense of inferior speed regulation [17]. Overall, Fleming et al. concluded that a more effective controller could be

produced by mixing the elements of the modified controllers and re-optimising [17].

As a closing statement, Fleming et al. recommended that inclusion of additional sensors, such as LIDAR, could improve results by using feedforward measurements to bypass the bandwidth limitation of the pitch controller [17]. The inclusion of LIDAR feedforward control for floating wind turbines was explored in [19] and [20], the results of which will be summarised in Section 4.6.

3   Methodologies

3.1   Paper selection process

For this review, papers were selected based on the extent of their use of LIDAR technology. Those which directly utilised real LIDAR measurements or simulated LIDAR measurements for the purpose of providing inputs for numerical model were deemed to be more applicable. Those which simulated "realistic" LIDAR measurements, accounting for measurement error and data processing, were also desirable.

In the case of academia, papers were selected from reputable journals (such as Wind Energy Science and the Journal of Physics) and conference proceedings (such as the American Control Conference (ACC), EERA DeepWind and The Science of Making Torque from Wind). Google Scholar was the primary search engine used to source academic literature for review. Common keywords used in searches were "Wind Turbines", "Floating", "Pitch Control", "Torque Control", "Yaw Control", "LIDAR-assisted", "Feedforward control" and "Preview Control". Papers and results which were released sequentially by the same authors or research group with increasing levels of complexity and building upon previous findings were sought. This provided a clearer picture to demonstrate how the field has developed as these groups and authors have shown a clear path and logical progression through their work. This continuity is especially useful to provide a coherent structure to the literature's progression. However, the focus should not only be on one author or group of authors and therefore, studies from separate authors have been sourced in order to compare against and supplement the core findings.

3.2   Data-basing and literature tree

As papers were sourced and read through, a summary was added to a database to track the key topics and findings for each study. This allowed for grouping of key themes and methodologies that were comparable across different studies, in order to build a catalogue of sources for particular areas. Papers were also critically assessed to determine how effectively their findings contributed to the field.

Upon adequate building of the database, a "literature tree" was created. This enabled the creation of a timeline to easily visualise the progression in the field, from conceptualisation to present day. Starting from the initial paper by Harris et al. [13], branches were created to categorise and link together themes and topics. Papers were categorised according to their main focus (e.g. pitch control), which allowed for clear visualisation of the volume of work conducted in each area to date, in addition to how sequential releases and different topics link to one another.

In writing this review, papers from each category were read to identify the key problem statement, methodologies and findings. These were collected sequentially and written up to form each subsection of Section 4. Evaluation has been included to add critique and review of the findings of the studies.

4   Results

This section begins with a summary table detailing the primary focus and key findings of studies that will be discussed. The table is clearly split to indicate studies performed on bottom-fixed turbines and those performed on floating offshore turbines. The table is also broken down to indicate whether the studies were focused on LIDAR-assisted torque, pitch or yaw control. The turbine operating regions that these apply to was discussed in subsection 2.2, and explanation for their modes are action can be found in [7].

Subsection 4.2 focuses on fixed turbine LIDAR-assisted pitch control and details results for various advanced control strategy implementations, including model predictive control (MPC), gain scheduling and individual pitch control. Subsection 4.2 will also detail the results of practical field tests that have been performed on bottom-fixed turbines. Subsections 4.3 and 4.4 detail results for LIDAR-assisted torque, and yaw control for fixed turbines, respectively. And Subsection 4.5 will discuss results for combined controllers which utilise control strategies across multiple operating regions. Subsection 4.6 will discuss the results of studies for floating turbines, which will only entail LIDAR-assisted pitch control as no studies have yet been published for LIDAR-assisted torque or yaw control of floating turbines.

4.1 Summary table

Table 1: Summary of reviewed LIDAR-assisted control papers and their findings, specifying whether the study was focused on bottom-fixed or floating turbines, the control mode, turbine rating and whether it utilised simulations or field testing on real turbines.

Ref.	Primary Focus	Year	Turbine Rating	Simulation or Field Testing?	Key Findings
Bottom-Fixed Turbine, Pitch Control					
[21]	Initial FF-FB study	2008	5 MW	Simulation	FF-FB control reduced rotor speed standard deviation by 70-80% compared to feedback only, leading to reductions in the fatigue and extreme loads on the tower, drive train and blades, whilst reducing the pitch rate.
[22]	FF-FB extreme loads	2011	5 MW	Simulation	Compared to feedback control, FF-FB control led to an 80% reduction in the deviation of the tower base fore-aft bending moment for an extreme operating gust.
[23]	Non-linear model predictive control (NMPC)	2013	5 MW	Simulation	Compared to feedback control, NMPC gave load reductions of up to 50% for extreme gusts and 30% for lifetime fatigue loads without negative impacts on the overall energy production.
[24]	Feedforward vs. NMPC	2012	5 MW	Simulation	The feedforward controller was less computationally complex whilst yielding similar performance improvements to the NMPC.
[25]	FF-FB vs FB	2015	5 MW	Simulation	FF-FB improved performance compared to feedback control through reduced pitch angle demand variation, tower fore-aft acceleration fluctuations and out-of-plane rotor torque without degrading the generated power.
[26]	Gain scheduled FF-FB	2016	5 MW	Simulation	Inclusion of gain scheduling allowed for greater load reductions on the rotor and tower than in [25] as well as reductions in pitch variations.
[27]	Filtered-X recursive least squares (FX-RLS) (Adaptive)	2011	600 kW	Simulation	FX-RLS gave improvements in tower and blade bending moments, rotor speed regulation and pitch rate, with negligible reductions in power production. Good performance was reported when realistic 1 and 5 Hz update rates were used - tower fore-aft bending moments were improved by 20.6% and blade flap-wise bending moment by 15.2%.
[28]	Feedforward individual pitch control (IPC) vs. FB	2010	5 MW	Simulation	Three IPC designs were found to allow for tighter regulation of power production and rotor speed vs. feedback only.
[29]	Field testing of LIDAR-assisted feedforward control	2013	600 kW	Field testing	Feedforward control showed greater rejection of the wind disturbance at low frequencies and reductions in the tower fore-aft bending, rotor torque, and collective flap bending when compared to feedback only control.
[30]	Field testing of LIDAR-assisted feedforward control	2014	600 kW	Field testing	Feedforward control gave positive impacts upon rotor speed regulation as well as on tower, blade and shaft loads compared to feedback only control.
Bottom-Fixed Turbine, Torque Control					
[31]	3 Torque control strategies vs. baseline	2013	600 kW	Simulation	The disturbance tracking control (DTC) and optimally tracking rotor (OTR) methods were found to slightly improve mean generator power capture when compared to the baseline controller, whilst worsening the low-speed shaft loads.
[32]	Region 2.5 performance of feedforward and DAC vs. baseline	2014	3 MW	Simulation	The controllers were unable to increase the averaged generator capture, but decreased the standard deviation of the rotor speed by approximately 6%, with minimal effects on the turbine structural loads.
Bottom-Fixed Turbine, Combined Control					
[33]	Control in Regions 2 and 3	2013	3 MW	Simulation	Region 2 - Increase in generator power of 3% and further decreases in tower base fore-aft bending moment damage equivalent loads (DELs) by up to 15%. Region 3 - 10% reduction in tower base fore-aft DELs without sacrificing power production or rotor speed regulations.
[34]	Flatness-based feedforward controller	2014	5 MW	Simulation	Load reductions on the tower (30%) and shaft (40%) at close to rated wind speed when compared to the baseline.
Bottom-Fixed Turbine, Yaw Control					
[12]	Power capture enhancement	2011	5 MW	Simulation	LIDAR-assisted yaw control gave a 1% expected increase in annual energy output when compared to measurements provided by a nacelle based anemometer.
[35]	Wind vane correction determination and comparison	2014	600kW	Field testing	With the error correction applied, results showed a significant increase in power capture and some positive and negative impacts upon loadings.
[36]	Direct Yaw control with LIDAR	2015	5 MW	Field testing	Wind vane yaw controller gave a 20 degree yaw misalignment but the LIDAR controller yaw misalignment was much closer to zero. The superior alignment was verified through a power performance analysis.
Floating Turbine, Pitch Control					
[19]	FF-FB control of floating turbine on a TLP	2015	5 MW	Simulation	Under wind speed step change, there was a reduction of extreme speed variation by 45% and the extreme tower displacement by 40% when compared to feedback only control. In a turbulent wind field with 5 m wave height, the standard deviation of the generator speed and loads were reduced by 44% and 24% respectively compared to feedback only control.
[15]	NMPC of floating turbine on a Spar	2013	5 MW	Simulation	Compared to feedback control, NMPC reduced tower loads and the rotor speed standard deviation by up to 90%.
[20]	Feedforward control of floating turbine on a Spar	2015	5 MW	Simulation	Perfect wind preview - the overshoot of the rotor speed could be reduced by 98.9%, the maximum deviation from the static platform pitch angle by 93.7%, and the maximum tower base fore-aft bending moment by 37.8% compared to the feedback controller. Realistic wind preview - Reductions in loads on the tower base of 20% were achieved as well as 7% and 9% reductions on the shaft and blade root loads respectively.

4.2 Bottom-Fixed turbines: LIDAR-assisted pitch control

The majority of the pitch control studies that have been published in the field of LIDAR-assisted control of wind turbines have been focused on fixed turbines. However, these studies underpin the work that authors have progressed on to publish for floating turbines.

An initial computational study of LIDAR-assisted FF-FB pitch control was performed by Schlipf and Khn [21], who found that the standard deviation of the rotor speed can be reduced by 70-80% compared to feedback only control. This can lead to reductions in the fatigue and extreme loads on the tower, drive train and blades, whilst reducing the pitch rate [21].

Their subsequent modelling research into collective pitch control focused on extreme loads [22]. For an extreme operating gust, when using FF-FB control, a reduction of 80% (compared to feedback control) in the deviation of the tower base fore-aft bending moment from the static value could be achieved [22].

4.2.1 Model predictive control

Other controllers have utilised model predictive control (MPC) [37][23]. MPC primarily operates using feedback control so does not require (although can still utilise) LIDAR but uses a model to determine predictions of future process outputs [38]. It is a holistic approach that can handle multiple-input,

multiple-output (MIMO) systems and constraints [38]. Its preview capability is analogous to that of feedforward control, and uses a "prediction horizon" to define the number of future time steps that it will consider [38]. However, the complexity of MPC is that it iteratively solves at each individual time-step, optimising to minimise the error. Schlipf et al. [23] found that a non-linear model predictive controller (NMPC) showed load reductions of up to 50% for extreme gusts and 30% for lifetime fatigue loads without negative impacts on the overall energy production.

Although MPC/NMPC have been shown to be effective for controlling the process and reducing loads, their significant drawback is their computational demand. Due to solving the model at each time step, the method requires a large amount of memory and a fast processor [38]. Therefore, in a subsequent study [24], the performance of a LIDAR feedforward controller was compared with the NMPC. Although the NMPC provided opportunity for designing an "optimal" controller, the feedforward controller was less computationally complex whilst yielding similar performance improvements to the NMPC [24].

4.2.2 Gain scheduling

Bao et al. [25] combined a model-inverse feedforward controller with a feedback controller and compared it to a baseline feedback controller. The combined FF-FB controller reduced pitch angle variations and reduced loads [25]. A limitation of this work was that the controller was only designed for a linearised operating point, meaning that performance could degrade when the turbine operated away from the operating point. Therefore, in a later study [26], they further developed their controller by implementing gain scheduling techniques for improvement of operation over a range of operating points. This improved controller was again augmented with the baseline feedback controller and LIDAR measurements were used to provide incoming wind data. Through the inclusion of gain scheduling to the FF-FB controller, further load reductions on the rotor and tower were achieved as well as reductions in pitch variations [26].

4.2.3 Adaptive control - Filtered-X Recursive Least Squares (FX-RLS)

In adaptive techniques, the control law can be updated at every time step according to the wind input conditions, meaning they can reject disturbances across a wider range of wind turbine operating points. Recursive least squares is a technique which recursively finds coefficients to minimise a weighted linear least squares cost function relating to the input signals [39]. Similarly to MPC, the computational demand is significant.

Wang et al. [27] developed a FX-RLS adaptive feedforward controller for use in conjunction with LIDAR. The controller was able to improve the tower and blade bending moments, rotor speed regulation and pitch rate, with negligible reductions in power production, when compared to the baseline feedback controller [27]. The controller also performed promisingly when realistic (those used by real LIDAR equipment) 1 and 5 Hz update rates were used, as the tower fore-aft bending moments were improved by 20.6% and blade flap-wise bending moment by 15.2% [27].

4.2.4 Individual pitch control

Dunne et al. [28] developed six feedforward individual pitch control (IPC) designs and compared them to an individual pitch, feedback-only baseline. These were evaluated on a 5 MW wind turbine model using realistic wind fields. Three of the individual

pitch feedforward controllers showed an improvement over the feedback only baseline. All of these incorporated a preview measurement of the incoming wind speed at three points ahead of the turbine, a scenario characteristic of LIDAR-assisted control. The three designs were found to allow for tighter regulation of power production and rotor speed [28] when compared to the feedback only baseline.

4.2.5 Field-testing of LIDAR-assisted pitch control

The studies discussed thus far have been computational LIDAR-assisted pitch control studies. However, there have been some deployments of LIDAR on wind turbines in the field for the purpose of practical turbine control. Scholbrock et al. [29] conducted field testing of LIDAR-based feedforward controls on the National Renewable Energy Laboratory's (NREL) Controls Advanced Research Turbine (CART) and found that this led to further rejection of the wind disturbance at low frequencies when compared to feedback alone. Schlipf et al. [30] also performed field testing of feedforward pitch control using LIDAR, finding positive impacts upon rotor speed regulation as well as on tower, blade and shaft loads. Although these works have highlighted the effectiveness of LIDAR assisted control in real-life applications, these tests were performed on 600 kW onshore turbines. To derive industrially applicable results, further studies should be performed on larger, commercial scale turbines.

4.3 Bottom-Fixed turbines: LIDAR-assisted torque control

The objective of torque control is to achieve power capture enhancement. Some studies have attempted to attain this through tracking of the optimal tip speed ratio, (λ_{opt}) [12][31]. The issue with controlling this by traditional means is that λ is not normally available as a control input and the control task is highly nonlinear [12]. This means that PI controllers cannot be used. However, when LIDAR is utilised, the tip speed ratio becomes measurable.

Schlipf et al. [12] proposed a feedforward update from LIDAR to compensate for incoming changes in the wind speed. This adjustment was able to maintain the optimal operation of the turbine through tracking of λ_{opt}. However, this came at the expense of substantial variation in the generator torque (which is used to vary the rotor speed) and only achieved a marginal increase in energy production. Damage equivalent loads (DELs) for the low speed shaft torque were also calculated and showed an increase of 34.7% [12].

Wang et al. [31] compared three LIDAR-enabled torque control strategies for turbine power capture enhancement. These were disturbance tracking control (DTC), optimally tracking rotor (OTR) and LIDAR-based preview control. DTC and Preview control were combined with a linear quadratic regulator (LQR) in the feedback path, while the OTR strategy was adapted from the quadratic $k\Omega^2$ feedback control [31]. The performance of these were all compared to the baseline $k\Omega^2$ feedback controller. The DTC and OTR methods were found to slightly improve mean generator power capture, whilst worsening the low-speed shaft loads [31].

Research has also been conducted into torque control in the transition region between Regions 2 and 3 (Region 2.5) [40]. Wang et al. [40] developed two LIDAR-based controllers, a nonlinear feedforward controller and a linear disturbance accommodating controller (DAC). The feedforward controller used the turbine's power coefficient surface to optimize the energy capture and the DAC used a LIDAR-measured wind speed instead of an estimate [40]. Although neither of the controllers were able to increase the averaged generator capture,

both were able to improve rotor speed regulation by decreasing the standard deviation of the rotor speed by approximately 6%, with minimal effects on the turbine structural loads [40].

At the time of writing, no studies have yet been published for the utilisation of LIDAR for feedforward torque control on floating turbines. However, the papers published for fixed turbines,may be used as a foundation for future work into LIDAR-assisted control of floating turbines.

4.4 Bottom-Fixed turbines: LIDAR-assisted yaw control

Studies have been performed to assess the benefit of LIDAR for increasing power capture with yaw control, mostly using field tests [12][35][36]. Schlipf et al. [12] explored the benefit of LIDAR for energy output by comparing measurements from a nacelle sonic anemometer to that of a scanning LIDAR system installed on a 5 MW turbine. When using the wind direction signal from the LIDAR instead of the anemometer, the expected increase in energy output was found to be 1% of the annual energy production from the wind turbine.

Fleming et al. [35] utilised LIDAR recorded data to determine an error correction value for the nacelle's wind vane's direction measurement. Tests were then performed to compare the performance of the turbine with and without the correction applied to the yaw controller. With the correction applied, results showed a significant increase in power capture and some positive and negative impacts upon loadings [35].

Similar work was conducted by Scholbrock et al. [36] but in this study, the LIDAR measurements were used to directly control the yaw direction and thus no error correction function was required. The wind vane yaw controller was found to have a 20 degree yaw misalignment, where as the LIDAR yaw controller had a yaw misalignment that was much closer to zero [36]. They verified this superior alignment through a power performance analysis. In below-rated speeds, the LIDAR yaw controller showed an improvement in power capture when compared to the nacelle yaw controller. However, there was more uncertainty at higher wind speeds because there was less data collected at those wind speeds. It was noted that the LIDAR controller was compared to a nacelle vane controller that did not include a yaw bias correction function. Had the LIDAR controller been compared to a nacelle vane controller that included a bias correction function, then the improvements were unlikely to have been as significant [36].

4.5 Fixed turbines: Combined controllers

Combined controllers aim to implement control mechanisms across multiple operating regions of a wind turbine, using a combination of pitch and torque control techniques. Wang et al. [33] investigated controllers designed to both mitigate tower fore-aft fatigue load in Region 3 and enhance power capture in Region 2 of a 3 MW turbine. In above rated conditions, a linear quadratic preview collective pitch control scheme paired with the baseline PI feedback controller was implemented. This achieved a 10% reduction in tower base fore-aft DELs without sacrificing power production or rotor speed regulation, though the pitch actuator usage was increased. In below rated conditions, a Lagrange multipliers optimization based feedforward control, combined with a pre-determined tower fore-aft feedback damping pitch controller, was investigated. This resulted in an increase in generator power of 3% and further decreases in tower base fore-aft bending moment DELs by up to 15%.

A flatness-based combined feedforward controller has also been proposed [34]. Using a simulated LIDAR device, the system constraints, which were the trajectories of the rotor speed and the tower movements, were continuously designed during operation. The flatness-based feedforward controller was combined with a conventional feedback controller. At close to rated wind speed, load reductions on the tower (30%) and shaft (40%) were reported.

4.6 Floating turbines: LIDAR-assisted control applications

Although the control concepts are transferable between fixed and floating wind, additional considerations have to be made for the negative damping caused by the coupling between the tower motions and the pitch control, as described in subsection 2.4. This imposes a bandwidth limitation on the pitch controller. It is possible to bypass this limitation by using feedforward measurements provided by nacelle-mounted LIDAR to increase the bandwidth [19][20]. The gains of the PI pitch controller can also be reduced to avoid the negative damping of the platform pitch motions [41].

Navalkar et al. [19] designed a robust FF-FB pitch controller for a 5 MW turbine on a TLP, assuming perfect LIDAR measurements. They noted that the high-bandwidth speed control may increase modal vibrations and thus aimed to design a controller to regulate generator speed without exciting the turbine modes [19]. The feedforward controller was designed under the assumption that the model was a perfect representation of the system and that the control effort can be arbitrarily large. It was noted that both assumptions have limited validity [19]. Under a wind speed step change, the robust FF-FB controller reduced extreme speed variation by 45% and the extreme tower displacement by 40% when compared to feedback only control [19]. They also investigated the performance during a turbulent wind field and with a wave height of 5 m. In this case, the standard deviation of the generator speed was reduced by 44%, and the standard deviation of the loads reduced by 24% compared to feedback only control [19].

Schlipf et al. furthered their studies into NMPC pitch control, described in [23][24], by performing studies on floating wind turbines [15][42]. In [15], they simulated their NMPC algorithm on a 5 MW Spar under irregular waves and under extreme and turbulent wind conditions. Tower loads could be reduced as well as the rotor speed standard deviation by up to 90%. It was concluded that this high-performing, computationally expensive controller can act as a benchmark for the development and comparison of less complex controllers [15].

Schlipf et al. [20] also simulated the implementation of LIDAR on a 5 MW floating wind turbine on a Spar foundation for collective pitch feedforward control. This implemented a feedforward controller that they had developed for onshore turbines [21][22] and subsequently tested in field testing campaigns [30]. The controller was adapted for floating turbines through inclusion of data processing and adaptive filtering stages. Filtering was implemented because only the low frequencies of the wind speed can be captured accurately by the LIDAR due to its motions on the nacelle. Tests were first performed assuming perfect wind preview. These resulted in significant improvements in turbine performance, as shown in Figure 4. For example, the overshoot of the rotor speed could be reduced by 98.9%, the maximum deviation from the static platform pitch angle by 93.7%, and the maximum tower base fore-aft bending moment by 37.8% compared to the feedback controller [20].
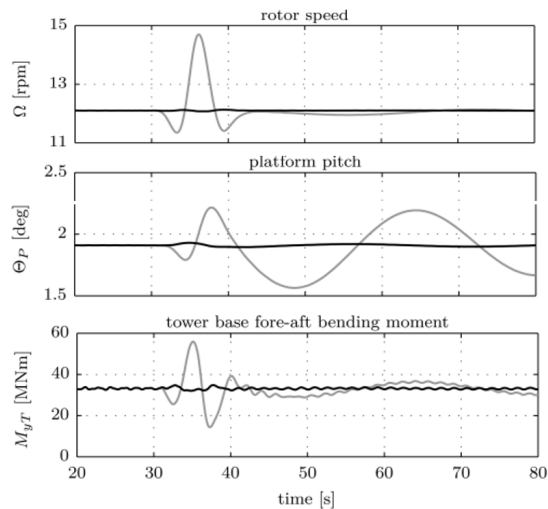
Figure 4: Results from [20], comparing performance of the feedforward (Black) to the baseline (Grey) controller with perfect wind preview.

Simulations were then performed under realistic conditions using a LIDAR simulator, developed in [43], to scan the wind field used in the numerical simulation. For applicability to floating turbines, the simulator was also extended to include platform motions in order to realistically reproduce LIDAR measurements from a floating wind turbine through calculation of the LIDAR's position, velocity and inclination based on the six platform and four tower modes, and their derivatives [20]. They reported that a good agreement was found between the rotor-effective wind speed from the wind field and its filtered, time-shifted estimate from the LIDAR (see Figure 5). Even with the more realistic wind preview, the rotor speed variation was still significantly reduced, in addition to the platform motions and the tower base bending moment [20]. Reductions in loads on the tower base of 20% were achieved as well as 7% and 9% reductions on the shaft and blade root loads respectively.
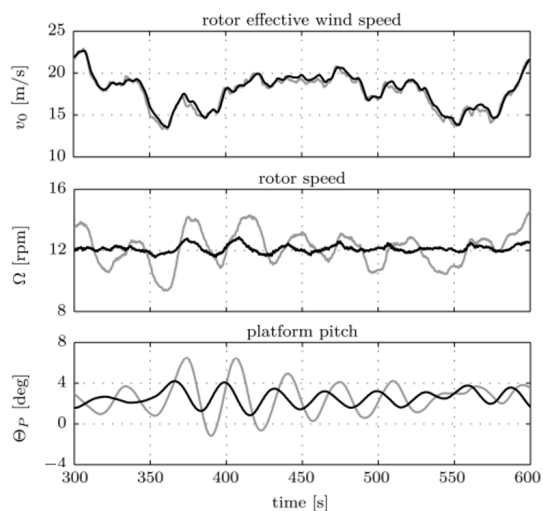

Figure 5: Results from [20]. Top: LIDAR captured (Black) vs. Simulated wind speed (Grey). Middle/Bottom: Comparing performance of the feedforward (Black) to the baseline (Grey) controller with realistic wind preview.

5   Future work recommendations

Although the studies reviewed in this paper have demonstrated LIDAR's promising potential for enhancing the performance of wind turbines with feedforward control, further research opportunities have been identified and will be summarised in this section. Due to the relative scarcity of publications focused on floating turbines, this section will primarily focus on the opportunities for future work that could be undertaken for floating turbines.

5.1   Design

Firstly, the largest turbine model studied in the published literature thus far is NREL's 5 MW reference turbine. However, turbine manufacturers have unveiled next generation models that will have capacities of at least 14 MW by 2024 [44][45][46]. Given that 10 MW and 15 MW reference turbines are available for use in numerical models, FF-FB control studies should be up-scaled to better reflect the direction of the commercial market.

In addition, the FF-FB control studies for floating turbines that were reviewed in Section 4.6 focused on turbines with TLP [19] and spar [15][20] foundations. To the best of the authors' knowledge, no studies have yet been published for semi-submersible foundations, which is the configuration deployed at the UK's largest floating wind farm (Kincardine, 50 MW). Further studies should be performed to investigate the benefit that LIDAR can provide for the control of turbines on semi-submersible substructures, with a view to reducing loadings and motions of the substructure. The results of such studies may also have implications for simplifying their design, particularly in terms of their weight and complexity of an internal control system.

5.2   Control

Given the prevalence of offshore wind shear (wind speed increasing with height), paired with the large rotor diameters (200m+) of the next generation turbines, their is expected to be significant variation in loads across the rotor disk of these turbines. Therefore, further studies should be performed that implement LIDAR-assisted individual pitch control, which can be used to control each blade's pitch angle to suit its position, and the varying loads that these incur, within the rotational plane.

No studies have yet been published in the literature for LIDAR-assisted yaw control of floating wind turbines. It is expected that the added yaw motion of the floating platform will render nacelle vane measurements subject to even greater errors and more frequent misalignment with the wind. LIDAR-assisted yaw control of floating turbines could therefore present a means to increase the power capture by ensuring alignment of the nacelle with the wind, with consideration of the platform motions. LIDAR-assisted yaw control could also be used to assist with wake steering (for wind farm control) and curtailment.

Due to larger turbine rotors and the slower speeds associated with them, turbine 1P and 3P frequencies will be lower and may come close to those for wave loading. Therefore, for floating turbines, it may also be important to consider the impact of wave loading on the performance of LIDAR-assisted floating turbines. Furthermore, knowledge of the incoming waves may also be useful for inputting into feedforward control algorithms for the control of floating turbines.

5.3 Commercial

Finally, to make LIDAR-assisted control modifications attractive and applicable to turbine manufacturers, a design case should be presented to show their practicality for commercial operations. This should not only demonstrate LIDAR's effectiveness for reducing loads, improving power capture, rotor speed regulation and yaw alignment across the full operating range, but also be easily adoptable by current and future turbine installations. This design case could be enhanced with a fatigue analysis, which could determine the component damage and failure rate reductions that can be achieved through LIDAR-assisted control. This can then be used to calculate the cost reductions attainable through implementation of the technology.

6 Conclusions

This paper has offered a review of LIDAR-assisted wind turbine control for both fixed and floating wind turbines. Published studies detailing LIDAR's capability to assist wind turbine's in their various control modes, including pitch, torque and yaw through addition of feedforward control to the existing feedback control loop have been reviewed.

Feedforward-feedback pitch control in above rated wind speeds has been shown to offer the most significant benefits when compared to feedback only control, particularly in terms of load reductions and rotor speed regulation, even under realistic LIDAR measurement uncertainties and data processing techniques. Feedforward-feedback torque control techniques have shown mixed results and have not resulted in significant increases in power capture. Utilising LIDAR for yaw control has been shown as an effective means of reducing the yaw misalignment and increasing annual power capture, due to LIDAR's capability to measure the wind direction. Enhanced control of the yaw of the turbines can aid in deliberate wake steering for wind farm control or for curtailment of turbines, when required. Field test studies of LIDAR-assisted control applications have also been reviewed and serve to support the findings of those reported in computational studies.

The challenges of translating control algorithms from fixed to floating turbines were discussed, particularly in terms of the negative damping that can occur due to the coupling between the tower and pitch dynamics. Studies within floating turbines have been primarily focused on LIDAR-assisted feedforward pitch control and have shown significant improvements in rotor speed regulation and tower fore-aft bending moment reduction.

Recommendations for future work have also been presented, including studies of LIDAR-assisted feedforward control for larger, commercial scale floating wind turbines (10 MW+). The need to expand the field into the study of individual pitch control, Semi-submersible substructures and coupling with knowledge of the incoming wave loading were also deemed to be potential areas for investigation. Finally, opportunities to undertake field-testing campaigns on offshore turbines should also be pursued, with a view to developing practical, implementable solutions for current and future installations. The case for this could be enhanced through quantification of the cost savings that implementation of the technology could achieve.

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