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List of Acronyms

Acronym	Name
CART-3	Controls Advanced Research Turbine, 3-Bladed
CSM	Colorado School of Mines
DAC	Disturbance Accommodating Control
DEL	Damage Equivalent Loads
DOE	Department of Energy
EEC	Extreme Event Control
EED	Extreme Event Detector
HAWT	Horizontal Axis Wind Turbine
LIDAR	Light Detection and Ranging
MAC	Michigan Aerospace Corporation
MPE	Maximum Permissible Exposure
NHZ	Nominal Hazard Zone
NOAA	National Oceanic and Atmospheric Association
NREL	National Renewable Energy Laboratory
NWTC	National Wind Testing Center
UNH	University of New Hampshire

Executive Summary

The goal of this Department of Energy (DOE) project is to increase wind turbine efficiency and reliability with the use of a Light Detection and Ranging (LIDAR) system. The LIDAR provides wind speed and direction data that can be used to help mitigate the fatigue stress on the turbine blades and internal components caused by wind gusts, sub-optimal pointing and reactionary speed or RPM changes. This effort will have a significant impact on the operation and maintenance costs of turbines across the industry. During the course of the project, Michigan Aerospace Corporation (MAC) modified and tested a prototype direct detection wind LIDAR instrument. Additionally, in co-operation with our partners, the National Renewable Energy Lab and the Colorado School of Mines, progress was made in LIDAR performance modeling as well as LIDAR feed forward control system modeling and simulation.

For this effort, MAC analyzed the requirements for wind turbine LIDAR mounting and operation. The resulting LIDAR design considered all aspects of wind turbine LIDAR operation from mounting, assembly, and environmental operating conditions to laser safety. The prototype instrument went through environmental and operational ground testing. The next generation LIDARs will incorporate the lessons learned from the prototype tests to create more rugged and reliable systems.

LIDARs, which can calculate wind speed at a distance by measuring the Doppler shift of laser light from scattered aerosols and air molecules in the atmosphere, can provide detailed wind field information to the turbine control system. The fundamental idea is that the LIDAR can detect extreme wind events at a distance, before they reach the turbine. Assuming its control architecture can accommodate this information, the turbine can take preemptive action to prevent an expensive Emergency Stop event or serious damage.

The turbine control research was performed using the Fatigue, Aerodynamics, Structures, and Turbulence (FAST) wind turbine simulator developed by the National Renewable Energy Laboratory (NREL). FAST can simulate operation of 2- or 3-bladed horizontal axis wind turbines (HAWTs), including the blade and tower loads. The results of this investigation showed that using LIDAR measurements to change between baseline and extreme event controllers in a switching architecture can reduce damage equivalent loads on blades and tower, and produce higher mean power output due to fewer overspeed events.

The LIDAR prototype testing and controller modeling results have been used to support the design of a Next Generation UV LIDAR (UV-Lite) that has the potential to dramatically improve the performance and lifetime of wind turbines. The Next Gen UV-Lite LIDAR is being built by OptoAtmospherics, a spin-off of Michigan Aerospace. The prototype has just completed successful wind tunnel testing at Michigan Aerospace. Discussions are underway with a turbine OEM regarding joint testing on a utility-scale platform at the National Wind Technology Center (NWTC). The goal of the testing is to demonstrate that integrated feed-forward LIDAR control is a viable solution for utility-scale turbines. This DOE project has led to continued venture capital investment and engagement with leading turbine OEMs, wind farm developers, and wind farm owner/operators.

Background

Current wind turbines use an anemometer and weathervane (or sonic anemometer) mounted on the turbine nacelle, generally downstream of the blades. Due to the extensive turbulence caused by the turbine's blade rotation and wake, the readings from the anemometers are severely influenced by the blades. In addition, each represents only a single point measurement and provides minimal knowledge of the flow field around and in front of the turbine. The current anemometers do not provide any warning of turbulent conditions, wind gusts, shear or veer. LIDAR has the potential to make a positive impact on turbine control and many other areas in the wind energy chain, including the following:

Turbine Control

- Active load mitigation through feed-forward measurements
- Gust, turbulence, and shear detection
- Turbine up-scaling for greater energy output
- Greater design margin and overall reliability
- Improved yaw control (new or retrofit) for improved energy capture

Asset Management

- Optimization of wind capture efficiency through feed-forward wind measurements
- Power curve measurement; wake effect analysis
- Intelligent, predictive data on energy availability from wind and other sources for improved load balancing

Site Assessment

- Improved measurement of turbulence, especially in complex terrain
- High-resolution wind, temperature, and density (simultaneously)
- Optimal turbine selection and placement
- Lower project risk through higher confidence in energy predictions

Project Objectives:

The purpose of this project is to increase turbine efficiency and reliability with the use of a ranging LIDAR system. This effort will have a significant impact on the operation and maintenance costs of turbines across the industry. The project objectives for this effort are as follows:

1. Optimize Michigan Aerospace's Direct Detection LIDAR for NREL turbine control input.
2. Enhance NREL turbine control system to accommodate range-resolved, atmospheric measurements.
3. Determine the effects on turbine control efficiency, operability and reliability using LIDAR measurements as a control system input.

The tasks for this project are shown in Table 1.

TABLE 1 PROJECT PLAN

Task	Technical Objective	Responsibility
Task 1: Requirements analysis	Objective 1	MAC/NREL
Task 2: Augment internal demonstration unit to accommodate NREL turbine control system	Objective 1	MAC
Task 2.1: Modeling and Simulation of LIDAR Turbine Control	Objective 2	NREL/CSM
Task 3: Modify NREL turbine control system to incorporate LIDAR atmospheric measurements	Objective 2	NREL
Task 4: Unit operational verification testing	Objective 3	MAC
Task 5: Field testing with NREL turbine (Deleted due to schedule and funds)	Objective 3	MAC/NREL
Task 6: Final report detailing effects of LIDAR atmospheric measurements for use in turbine control	Objective 3	MAC/NREL

Team Qualifications:

Michigan Aerospace Corporation:

Michigan Aerospace Corporation is the premier company in the United States for the development of Light Detection and Ranging (LIDAR) and related optical systems for atmospheric measurement and holds patents that increase the performance and efficiency of these instruments to unprecedented levels. Since its founding, MAC has developed a variety of LIDAR systems. Prominent among these is the GroundWinds project. This initiative to demonstrate direct-detection fringe imaging Doppler wind LIDAR technology is funded by the National Oceanic and Atmospheric Administration (NOAA) through the University of New Hampshire (UNH). The program sought to demonstrate this technology for application to future space-based global tropospheric wind sounding. The GroundWinds program has successfully demonstrated two ground-based instruments, which were designed and built by MAC. The first LIDAR, GroundWinds New Hampshire, is located at the base of Mount Washington and operates at 532 nm. The second, GroundWinds Hawaii, is located near the summit of Mauna Loa at the NOAA observatory and operates at 355nm. Both of the GroundWinds systems detect Doppler shifts in the atmosphere from the ground up to 20 km in altitude above their sites. The GroundWinds system images the full backscattered spectrum from atmospheric molecules and aerosols. MAC has further developed this technology to be much more compact for applications on aerial platforms as well as on size- and weight-limited ground and marine platforms.

National Renewable Energy Laboratory:

The National Renewable Energy Laboratory's (NREL's) National Wind Technology Center (NWTCT), located at the base of the foothills just south of Boulder, Colorado, is the nation's premier wind energy technology research facility. Built in 1993, the center provides an ideal environment for the development of advanced wind energy technologies. The goal of the research conducted at the center is to help industry reduce the cost of energy so that wind can compete with traditional energy sources, providing a clean, renewable alternative for our nation's energy needs.

One of the specific areas of research at NREL is in development of advanced control algorithms for wind turbine fatigue load mitigation and enhanced power capture. As today's utility-scale wind turbines become taller and more flexible, NREL researchers are investigating ways to mitigate system fatigue by gaining better control of the way the components interact and move. NREL conducts systems and controls research to increase energy capture and reduce structural loading for minimal cost. By studying conventional turbine component controls such as blade pitching, new components such as twist-coupled blades, and advanced devices such as micro-tabs, researchers are developing innovative rotor control strategies to mitigate unwanted aerodynamic loads at the rotor hub and investigating ways to improve design codes.

Results and Discussion

The discussion of project activities and results can be divided into two main sections, LIDAR Requirements and Prototype Build/Test and LIDAR Wind Turbine Control Simulation. Each section will outline the approaches used to meet the program objectives, problems that were encountered, conclusions and recommendations.

LIDAR Requirements and Prototype Build/Test

LIDAR Overview

Range imaging, UV direct detection technology offers many advantages over other LIDAR technologies currently available, including the ability to have 100% up-time and multiple fields of view providing simultaneous range-resolved measurements of the wind. One of the key differentiators is the use of UV wavelengths, which enables the measurement of air molecules in addition to that of aerosols. This allows operation in completely clear air, devoid of aerosols (dust, water vapor, etc.), which can occur after a heavy rainfall, for example. It also allows operation in environments where aerosol concentration is normally low. The technique also allows the separation of molecular and aerosol return signals, enabling true wind speed measurements during rainfall when the aerosol velocity may differ from the air velocity. As shown in the picture of Figure 1, UV laser light is emitted into the atmosphere where it scatters off the molecules and aerosol. The LIDAR collects the backscattered light and images the resulting fringes onto a CCD. The image is analyzed to compare the return signal with the laser reference to determine, wind speed, direction, temperature and density. A functional diagram of the range-imaging LIDAR is shown in Figure 2.

FIGURE 1 LIDAR OVERVIEW

FIGURE 2 RANGE IMAGING, DIRECT DETECTION LIDAR FUNCTIONAL OVERVIEW

Instrument Description

Figure 3 illustrates the implementation of a turbine-mounted LIDAR. The system will be mounted on top of the nacelle with sufficient height to allow a 15 degree cone angle. The LIDAR consists of four independent fields of view spaced 90 degrees from one another around the cone. The four fields of view will measure the wind at approximately 2/3 of the distance from the center-line to the blade tip at 100m (range bin #9). This is how the 15 degree cone angle was selected. The system also measures 10 range bins for each of the four lines of sight simultaneously, providing a true "snapshot" of the wind field. The maximum range of the system was chosen to be 200m. The instrument is capable of ranges up to 1km using the same architecture. The purpose of 10 range bins is to provide greater spatial resolution for turbulence, shear, and gust tracking ETA. Having four independent fields of view also aids in the true measurement of the flow field since there is no delay due to scanning. The current location of the center of each range bin is provided in Figure 3. Also included is the size (maximum and minimum measurement distance) associated with each range bin. The contribution to the measurement as a function of distance for each range bin is shown in Figure 4. Note that a majority of the return signal or measurement is around the center of each range bin and that the edges of the range bin size contribute much less to the return signal.

FIGURE 3 PROPOSED IMPLEMENTATION OF TURBINE MOUNTED LIDAR

FIGURE 4 RANGE BIN DISTRIBUTION

Requirements

The requirements for the turbine-mounted LIDAR system consist of four levels: Customer requirements, system requirements, subsystem requirements and component specifications. The hierarchy of these requirements is shown in Figure 5. Customer requirements are the most fundamental requirements that serve to initiate the flow down process. These requirements are derived from the needs of turbine OEM customers. While some of the requirements, such as electrical power and space constraints, are well-defined, others, such as required accuracy, update rate, range and number of measurements, are estimates based on what the customer anticipates will be necessary. System requirements are derived from customer needs and/or requirements but are also driven by competitors' capabilities and our understanding of the range of possible atmospheric flow field conditions. The subsystems have been defined as the following: mechanical, optical, electrical and software. Requirements are derived from the system-level requirements based on how they would affect each of these subsystems. Component specifications are then constructed based on the subsystem requirements.

Product specifications with respect to the environment, general hazard and safety have been developed in coordination with turbine OEMs.

FIGURE 5 REQUIREMENTS FLOWDOWN

The flow down of the requirements from the customer all the way down to the component level is shown in Table 2. Specifically, the table shows how the system requirements were derived from the customer requirements. The following section details the subsystem and component-level requirements, both derived from the system level as well as requirements inherent to the design and technology itself.

TABLE 2 REQUIREMENTS

Parameter	Customer Requirements / Needs	System Requirements	Sub-systems influenced	Components influenced
1. Reliability (System up-time)¹	>98% (100% objective) ²	UV operation (<405nm)	Optical and electrical	Laser, lenses, mirrors, filters, etalon and detector
		High reliability components (Reliability analysis required)	Mechanical, optical, electrical and software	All components
2. Maintenance	>20,000 hours MTTR (degradation expected; line replaceable unit servicing TBD) ³	Field maintainable, serviceable	Mechanical, optical, electrical and software	Laser, lenses, mirrors, filters, windows, etalon and detector
3. Wind speed accuracy	1 m/s ⁴	Trade between laser power, telescope aperture and update rate to achieve 1m/s	Mechanical, optical, electrical and software	Laser, lenses, mirrors, filters, etalon and detector
4. Range	100m (200m nominal) ⁵	Cross eye and separation between outgoing laser and telescope field of view selected to achieve >200m range	Mechanical and optical	Mechanical support (front plate size) and lenses
		Trade between laser power and telescope aperture to provide sufficient backscatter to achieve >200m range	Mechanical, optical, electrical and software	Laser, lenses, mirrors, filters, etalon and detector
5. Update rate	0.25Hz-1Hz+ (1Hz objective) ⁶	Trade between laser power, telescope aperture and accuracy to achieve 1Hz	Mechanical, optical, electrical and software	Laser, lenses, mirrors, filters, etalon and detector
		Processing and transfer of data must take place in less than one second	Electrical and software	Detector and data processing electronics

¹ It should be noted that a full system reliability analysis has not been performed² Estimate; requires validation by customer and reliability analysis; maintenance to turbine nacelle systems by service personnel is typically no greater than every 6mos³ Estimate; requires validation by customer, reliability analysis, and economic analysis⁴ Ibid⁵ Initial requirement based on customer desire to validate against instrumented MET tower, 100m from turbine hub.⁶ Estimate; requires validation by field testing

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Parameter	Customer Requirements / Needs	System Requirements	Sub-systems influenced	Components influenced
6. Wind loading /mapping	Gust/shear detection	Multiple lines of sight(4)	Mechanical, optical, electrical and software	Laser, lenses, mirrors, filters, etalon, detector and data processing electronics
		Multiple range bins (>5) per line of sight	Mechanical, optical, electrical and software	Laser, etalon, lenses, mirrors, filters, detector and data processing electronics
	Measurement at 2/3 blade chord length at 100m ⁷	15° outward measurement angle from central axis	Mechanical and optical	Mechanical support and lenses
7. Laser safety	Eye-safe at ground level or on adjacent turbines (at ~500m)	Expansion of outgoing beam	Mechanical and optical	Mechanical support, laser, lenses, mirrors and beam expander
		Divergence of outgoing beam	Mechanical and optical	Mechanical support, laser, lenses, mirrors and beam expander
		Limited scanning (<1° every 10 minutes)	Mechanical, optical, electrical and software	Mechanical support, laser and gimbal mechanism
8. Environmental	All-weather operation	NEMA 4 rated enclosure or comparable custom enclosures	Mechanical	All mechanical enclosures (custom and off-the shelf)
		Thermal control system/design adequate to keep critical components within spec	Mechanical, electrical and software	System controller, air conditioning units, sun shield, laser and detector
		Measurement in adverse conditions (rain, fog, etc...)	Mechanical, optical, electrical and software	Detector, beam expander and data processing electronics
	System must operate in turbine vibration environment	System must remain aligned and locked down during vibration. Vibration isolators may be necessary for sensitive components	Mechanical	All mechanical support structure and vibration isolators

⁷ Initial requirement based on customer desire to validate against instrumented MET tower, 100m from turbine hub.

Final Report

Parameter	Customer Requirements / Needs	System Requirements	Sub-systems influenced	Components influenced
	System must operate in turbine EMI environment	System must continuously operate and not be susceptible to possible EMI	Mechanical, electrical and software	Mechanical seals, electronics sensitive to EMI
9. Size and weight	Individual components/sub-assemblies being lifted must be below 200lbs (91kg) ⁸	Weight of components/sub-assemblies are limited to 200lbs (91kg)	Mechanical, optical and electrical	All components (NEMA enclosure and optical head are limited sub-assemblies)
	All components/sub-assemblies must fit through nacelle hatch (720mm x 750mm) ⁹	Components/sub-assemblies are limited to 200lbs (91kg)	Mechanical, optical and electrical	All components (NEMA enclosure and optical head are limited sub-assemblies)
10. Power	Power will be provided at 230V / 50Hz with a maximum of 12A ¹⁰	Voltage converter required for some off the shelf components	Electrical	UPS, voltage converter and all electrical components
	Power supply may not be clean, UPS recommended initially ¹¹	UPS required	Electrical	UPS and all electrical components
11. Delivery	Instrument must be installed on turbine during turbine test phase ¹²	Implement as many off-the shelf solutions as possible to meet delivery schedule. Customization is limited	Mechanical, optical, electrical and software	All components

⁸ Based on initial customer lifting constraints⁹ Based on initial customer¹⁰ Based on initial customer¹¹ Based on initial customer¹² Based on initial customer

Prototype LIDAR Build

The prototype Turbine Mounted Wind LIDAR instrument consists of the following modular components. These components will be installed either on top of the turbine nacelle or within the nacelle in an electronics rack, as indicated below.

Externally-Mounted:

1. Transmitter/Receiver Optical Head
2. Hutton DDB-OD-16DDC electrical cabinet containing:
 - Laser Power Supply
 - Camera control electronics
 - Ice Qube IQ1000V BTUH cooling fans
3. Electrical-Fluid Feedthrough Panel
 - 6 Electrical Bulkhead Connectors
 - 2 Quick Connect Fluid Feedthroughs

Internally-Mounted (16 U total):

1. 3U Rack Mount Control Computer
2. 2U Rack Mount Uninterruptible Power Supply
3. 4U Rack Mount Laser Chiller
4. 2U Rack Mount System Control Electronics
5. 3U Rack Mount Power Distribution Box
6. 1U Rack Mount Air Circulation Unit
7. 3U Rear Rack Mount Connector Interface Panel
8. Rear Rack Mounted Network Hub

Figure 6 and Figure 7 illustrate the integrated prototype turbine mounted wind LIDAR instrument external components.

FIGURE 6 FRONT VIEW OF OPTOATMOSPHERICS TURBINE MOUNTED WIND LIDAR INSTRUMENT

FIGURE 7 SIDE VIEW OF OPTOATMOSPHERICS TURBINE MOUNTED WIND LIDAR INSTRUMENT.

The optical head houses the core instrument, the receive optics, the laser head, the beam expander and outgoing beam-shaping optics. It consists of a central 2" thick aluminum plate that supports the core instrument's optics and detector. Attached to the base plate are two vertical endplates. The front contains windows for both the outgoing laser beams and incoming backscatter telescopes. The entire assembly is encapsulated with two sheet metal covers (top and bottom) that provides access to the internal components if necessary. There

is a secondary solar shield cover that is air-gapped at 0.5" from the top cover. Figure 8 shows the constructed optical head.

FIGURE 8 OPTICAL HEAD ENCLOSURE (SHOWN WITH GIMBAL)

Figure 9 provides the dimensions for the two units installed on the I-beam rail in the nacelle. The included components are shown in Figure 10.

FIGURE 9 DIMENSIONS OF THE DATA PROCESSING AND UPS/CHILLER UNITS

FIGURE 10 COMPONENTS IN DATA PROCESSING AND UPS/CHILLER UNITS

System Interconnect Diagrams

The cabling and electrical connections of the system are detailed in Figure 11.

FIGURE 11 SYSTEM INTERCONNECT DIAGRAM

Environmental Testing

The prototype LIDAR went through a regime of environmental testing. A summary of the test type and parameters are shown in Table 3.

TABLE 3 ENVIRONMENTAL TESTING SUMMARY

Test Type	Parameters	Notes
Thermal Testing	20 °C to 50 °C	Ramp and Dwell while taking reference data
Vibration	1. 5 to 40 Hz Broad-Spectrum Scan 2. 0 to 10Hz Narrow-Spectrum Scan 3. 5 to 200 Hz Broad-Spectrum Scan 4. Random Vib Stress Test: 50 to 200 Hz random with a maximum load of 1.0 g. 5. 50 to 70Hz Narrow-Spectrum Scan 6. 110 to 1250Hz Narrow-Spectrum Scan 7. 5 to 200 Hz Broad-Spectrum Scan 8. Random Vib StressTest: 5 to 500 Hz with a total magnitude of 2.0 g	Series of sinusoidal and random vibration tests to evaluate the modal frequencies inherent in the LIDAR system optical head, gimbal structure, and external electronics enclosure
EMI-EMC	10 volt/meter @ several directions	UL testing - Tested Optical Head and Electronics Racks

Open Air Testing Results and Conclusions

Michigan Aerospace performed tests with the prototype LIDAR in open air, in simulated rain conditions, and also looked at laser impingement effects with a simulated turbine blade. Figure 12 shows a collected fringe image from the LIDAR instrument. The arms of the 'X' represent the 4 different fields of view of the LIDAR. Each arm has laser reference spectra and the backscattered sky return spectra. The difference in laser shift between the sky return and the laser reference represents the line-of-sight wind speed. Figure 13 is a plot showing good agreement between the LIDAR measured wind velocity and the local anemometer reading.

FIGURE 12 LIDAR DATA COLLECTION

FIGURE 13 OUTSIDE DATA: FIRST CHART – ONE CHANNEL, RANGE BINS 4 & 5 AT 1-SECOND INTEGRATION; REPRESENTATIVE DATA (ALL FOUR CHANNELS)

MAC completed the planned ground tests of the LIDAR instrument. The lessons learned during testing of this prototype are being incorporated into the next generation of LIDAR, which is in the process of final assembly and test.

LIDAR wind turbine control simulation

Michigan Aerospace provided a LIDAR model to NREL and the Colorado School of Mines (CSM) to aid in wind turbine control strategy simulations. As part of this research effort, Andrew Pace at CSM developed methods for using LIDAR systems with different wind turbine control schemes to decrease mechanical loads with decreasing generated power, the ultimate being extreme event control—namely, to prevent emergency shutdowns caused by rotor overspeed, which are quite costly.

We summarize here the major results of Andrew's research as it relates to the integration of LIDAR technology into wind turbines. Much of what follows is based directly on the text of his thesis. For a copy of the full thesis, which contains details beyond this brief overview, please contact MAC Vice President Dr. Matthew Lewis at mlewis@michaero.com.

The Problem

In order for wind power to become more competitive, the price of wind energy must decrease. There are many methods for doing this: increasing turbine efficiency; reducing turbine construction costs; and increasing turbine lifetime. The last point, increasing turbine lifetime, is the focus of this research.

With respect to increasing turbine lifetime, perhaps the most important factor is reducing turbine loads, especially for large, utility-scale turbines, since they are particularly susceptible to large loads. In any wind turbine operation there are two primary regions of operation¹³, as shown in Figure 14.

FIGURE 14: THE REGIONS OF WIND TURBINE OPERATION.

¹³ J.F. Manwell, J. G. Mcgowan, and A. L. Rogers. *Wind Energy Explained: Theory, Design, and Application*. Wiley, 2nd Edition. 2009.

The first is called Region 2; it is the region where power production tracks wind speed. The second, called region 3, is where power production is regulated to a rated power, independent of wind speed.

Region 2 is characterized by fixed pitch and variable generator torque. Control in this region is aimed at maximizing aerodynamic efficiency, extracting from the lower wind speeds as much energy as possible. In Region 3, which is the primary focus of this research, control systems vary the pitch angle in order to achieve approximately constant generator torque. The goal of Region 3 controllers is to reduce the cost of wind energy by reducing loads while producing constant power.

Sudden excessive loads can cause an Emergency Stop event. For example, an excessive load event may cause the rotor to spin too rapidly, causing a supervisory controller to issue an emergency stop to protect the turbine. Because the wind turbine must then be restarted, often manually, these events are expensive, and increase the cost of wind energy.

LIDAR Based Solutions

One solution to reducing loads is to provide more detailed wind field information to the turbine control system. LIDARs, which can estimate wind speed at a distance by measuring the Doppler shift of laser light from scattered aerosols and air molecules in the atmosphere, can provide this detailed information.

The fundamental idea is that LIDAR detects extreme wind events at a distance, before they reach the turbine. Assuming its control architecture can accommodate this information, the turbine can take preemptive action to prevent an expensive Emergency Stop event or serious damage. The trick is developing a control architecture that can best make use of this new LIDAR information.

The fundamental contributions of the research described below are:

1. An investigation of different methods for incorporating LIDAR with measurements within Disturbance Accommodating Control (DAC) architectures.
2. An investigation of gain scheduling using LIDAR measured wind speeds.
3. The design of switching controllers/mechanisms to prevent rotor overspeed while not unnecessarily exciting mechanical modes in the turbine.

The Simulation Environment

The research was performed using the Fatigue, Aerodynamics, Structures, and Turbulence (FAST) wind turbine simulator developed by the National Renewable Energy Laboratory (NREL). FAST can simulate operation of 2 or 3-bladed horizontal axis wind turbines (HAWTs), including the blade and tower loads.

The Controls Advanced Research Turbine, 3-Bladed (CART-3) research turbine was used as the model for the simulated wind turbine in this research. Only a subset of the available degrees of freedom was enabled. The final state space linear model consisted of five states:

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix} = \begin{bmatrix} \text{Drive train torsion} \\ \text{Collective blade flap displacement} \\ \text{Generator speed} \\ \text{Drive train torsional velocity} \\ \text{Collective blade flap displacement velocity} \end{bmatrix}$$

For its LIDAR component, this research used the FAST-compatible LIDAR developed by Simley, *et al.*¹⁴ The LIDAR is presumed to be hub-mounted, pulsed, and with the first range gate at **36 m**, with a second at **72 m**, pointing straight upwind, as illustrated in Figure 15.

FIGURE 15: THE MODELED PULSED LIDAR CONFIGURATION WITH ONE BEAM AND TWO RANGE GATES.

To simulate the wind itself, various wind files were presented to the simulation. The wind files implemented one of three different sorts of wind fields: 1) stepwise constant winds; 2) extreme operating gusts (EOGs); and, 3) turbulent wind. These three types are illustrated in Figure 16.

FIGURE 16: EXAMPLE WIND FILES: (A) STEPWISE CONSTANT; (B) EOG WITH STEADY WIND SPEED OF 18 M/S; AND, (C) TURBULENT WIND.

Metrics

In order to assess the efficacy of different control schemes, this research employs four different metrics:

1. Mean generated power for a given wind file;
2. Damage equivalent loads (DELs) on the rotor blades' edgewise and flapwise bending moments;
3. DELs on the tower's base fore-aft (FA) and side-to-side bending moments; and,
4. Number of overspeed occurrences.

¹⁴ E. Simley, et al. Analysis of wind speed measurements using continuous wave LIDAR for wind turbine control. In *Proceedings of the AIAA Aerospace Sciences Meetings*, Orlando FL, January 2011.

Wind Turbine Control

Since the focus of this research is Region 3 control, the primary method of control is through blade pitch angle. In addition to a normal operation controller, the CART-3 (and utility scale turbines as well) has a supervisory controller, the purpose of which is to protect the wind turbine during the testing of new controllers. The controller continually checks for faults—when one is detected, it switches to a shutdown controller. The process is depicted in Figure 17.

FIGURE 17: GENERALIZED SUPERVISORY CONTROL. WHEN A FAULT IS DETECTED, CONTROL SWITCHES FROM THE OPERATIONAL CONTROLLER TO A SHUTDOWN CONTROLLER. THE SEVERITY OF THE FAULT DETERMINES IF A NORMAL OR EMERGENCY STOP IS TRIGGERED.

We present an example of supervisory control in Figure 18.

FIGURE 18: GENERATOR TORQUE AND BLADE PITCH ANGLES DURING AN EMERGENCY STOP ON CART-3 FROM A FIELD TEST. THE VERTICAL RED LINE INDICATES WHEN THE EMERGENCY STOP OCCURRED.

Disturbance Accommodating Control

Disturbance Accommodating Control (DAC) is a control architecture that estimates disturbances to a system, and uses these estimates in the control law. Previous work on wind turbine control has demonstrated DAC-based control schemes are superior to industry standard methods¹⁵. Furthermore, the integration of LIDAR with DAC has been shown to reduce blade root bending moments by 10% compared to DAC without LIDAR¹⁶. In that

¹⁵ A.D. Wright, et al. Progress in Implementing and Testing State-Space Controls for the Controls of Advanced Wind Turbine Research. In *Collection of the 2005 ASME Wind Energy Symposium Technical Papers at the 42nd AIAA Aerospace Sciences Meeting and Exhibit*. Pages 88-100. American Institute of Aeronautics and Astronautics, Inc. (AIAA) and the American Society of Mechanical Engineers (ASME), 2004.

¹⁶ M. Harris, et al. Lidar for Turbine Control. *Technical Report NREL/TP-500-39154*. National Renewable Energy Laboratory. Golden, CO. January 2006.

work, the turbine model was a nonlinear 2-bladed wind turbine with flap-bending and generator degrees of freedom. The LIDAR measurements were used to estimate vertical shear, and these measurements were used directly by the controller instead of being fed into an estimator, particularly in the presence of turbulent wind flow. In its standard configuration, DAC has the following form:

$$\begin{aligned}\dot{\hat{x}} &= A\hat{x} + K(y - \hat{y}) + B_d\hat{u}_d + Bu \\ \hat{y} &= C\hat{x} \\ \dot{\hat{z}}_d &= F\hat{z}_d + K_d(y - \hat{y}) \\ \hat{u}_d &= \Theta\hat{z}_d\end{aligned}$$

where the control signal, u , is calculated as:

$$u = G\hat{x} + G_d\hat{z}_d.$$

The parameters A, B, C, B_d is the state space representation for the linearized plant; K, K_d are the estimator gains for the state and disturbance observers, respectively; and G, G_d are the feedback gains the plant and the disturbance.

The basic architecture of a DAC-based system is presented in Figure 19, and an example of the rotor speed response for the DAC is shown in Figure 20.

FIGURE 19: THE BASIC ARCHITECTURE OF A DAC.

FIGURE 20: ROTOR SPEED RESPONSE FOR THE DAC WITH LINEARIZATION AROUND 13 m/s WIND SPEED.

We directly accommodate a LIDAR by modifying our state equations:

$$\begin{aligned}\dot{\hat{x}} &= A\hat{x} + K(y - \hat{y}) + B_d w_{measured} + Bu \\ \hat{y} &= C\hat{x}\end{aligned}$$

where $w_{measured}$ is the wind speed's deviation from the operating point, as measured by the LIDAR. The control law is then:

$$u = G\hat{x} + G_d w_{measured}$$

The control architecture that accommodates direct LIDAR input is shown in Figure 21. In simulations with the use of LIDAR feedback into the estimator, rotor speed regulation is achieved, but the output estimation error is quite high. DAC without LIDAR is able to achieve both rotor speed regulation and good output estimation—though the use of LIDAR does provide better estimates of wind speeds.

Since none of the methods for incorporating LIDAR directly into the DAC produced good regulation and good estimation, it was decided to focus LIDAR for use in a switching-based extreme event control (EEC), as described in the next section.

FIGURE 21: WE REPLACE THE DISTURBANCE ESTIMATOR WITH DIRECT LIDAR MEASUREMENTS. THE DISTURBANCE MODEL IS THAT OF A STEP, WITH THE MEASUREMENT BEING THE DIFFERENCE BETWEEN THE LIDAR MEASURED WIND SPEED AND THE LINEARIZATION POINT OF 18 m/s.

Switching From Baseline DAC to EEC

Another approach to load reduction is to introduce a switching controller—a controller that detects the onset of an extreme event, and switches from a baseline controller to an appropriate extreme event controller. This architecture is illustrated in Figure 22.

FIGURE 22: ARCHITECTURE OF AN EXTREME EVENT CONTROLLER.

For most of the time, the baseline DAC is used. A LIDAR unit measures wind speed at hub height 72 m in front of the turbine. The LIDAR wind measurements are used by the Extreme Event Detector (EED) to determine when a large wind gust is approaching the turbine. When such a gust is detected, operational control of the turbine is switched from the

baseline DAC to an EEC. When the gust has passed the turbine, control authority is transitioned back to the baseline DAC from the EEC.

In order to determine if a gust is imminent, a one-sided CUSUM algorithm evaluates LIDAR measurements to detect significant increases in wind speed. The algorithm is tuned to be sensitive to short, sharp increases in wind speed, and selected to work with a LIDAR system with a 1 Hz update rate.

To test the effectiveness of the switching controller at preventing rotor overspeed due to extreme gusts, gusts were simulated. Turbine response for both DAC-only and the switching controller were compared. The results are presented in Figure 23. Since the switching controller prevented more overspeeds than the baseline DAC, the mean generate power is higher by 18% over 12 wind test files. Overall, the damage equivalent loads (DELs) are lower for the switching controllers, as well. This indicates that for extreme operating gust (EOG) conditions, switching can reduce turbine loads, even in cases where overspeed does not occur.

Control Modeling Conclusions

The results of this research points to the utility of including LIDAR based measurements to help prevent turbine overspeed shutdowns. Although the inclusion of LIDAR measurements directly in DAC-based architectures achieves the desired rotor speed regulation, the output estimator error is unacceptably high. However, when used to switch between baseline and extreme event controllers in a switching architecture, LIDAR measurements can reduce damage equivalent loads on blades and tower, and produce higher mean power output due to fewer overspeed events.

FIGURE 23: SUMMARY RESULTS FOR EXTREME OPERATING GUST (EOG) SIMULATIONS FOR BASELINE (BL) AND SWITCH (SC) CONTROLLERS. SINCE THE BL DAC STRATEGY RESULTED IN MORE EMERGENCY STOPS, MEAN POWER GENERATED IS LOWER, AND TOWER LOADS (DELS) ARE HIGHER.

Accomplishments

The project objectives for this effort were as follows:

1. Optimize Michigan Aerospace's Direct Detection LIDAR for NREL turbine control input.
2. Enhance NREL turbine control system to accommodate range-resolved, atmospheric measurements.
3. Determine the effects on turbine control efficiency, operability and reliability using LIDAR measurements as a control system input.

The program accomplishments have been previously discussed and Table 4 below references the report section that covers each task and objective.

TABLE 4 PROGRAM OBJECTIVES

Task	Technical Objective	Discussed in Section
Task 1: Requirements analysis	Objective 1	Requirements – pg 5
Task 2: Augment internal demonstration unit to accommodate NREL turbine control system	Objective 1	Prototype LIDAR Build pg 16
Task 2.1: Modeling and Simulation of LIDAR Turbine Control	Objective 2	LIDAR wind turbine control simulation -pg 23
Task 3: Modify NREL turbine control system to incorporate LIDAR atmospheric measurements	Objective 2	LIDAR wind turbine control simulation – pg 23
Task 4: Unit operational verification testing	Objective 3	Environmental Testing – pg 20 Open Air Testing Results and Conclusions – pg 21
Task 5: Field testing with NREL turbine Deleted due to schedule and funds	Objective 3	MAC/NREL
Task 6: Final report detailing effects of LIDAR atmospheric measurements for use in turbine control	Objective 3	LIDAR wind turbine control simulation pg 23

During the course of the project, Task 2.1 Modeling and Simulation of LIDAR Turbine Control was added to the Statement of Work. Michigan Aerospace, NREL staff, and researchers from the CSM were involved in this modeling, simulation, and analysis effort. LIDAR models were integrated with the turbine control system and simulations were run to examine trades and predict performance under various conditions.

Commercialization efforts are discussed in the following section, Conclusions and Recommendations.

Conclusions and Recommendations

Through the support of DOE and our partners, the National Renewable Energy Lab and the Colorado School of Mines, successful UV LIDAR prototype testing and feed-forward control system modeling and simulation have been performed. The results have been used to refine the design of a Next Generation UV LIDAR (called UV-Lite) that has the potential to dramatically improve the performance and lifetime of wind turbines. This capability has enabled Michigan Aerospace to spin off a company, OptoAtmospherics, to focus on wind energy applications and has led to venture capital investment and multiple rounds of funding. A prototype of the Next Gen UV-Lite LIDAR is being built by OptoAtmospherics. The prototype has just completed successful wind tunnel testing at Michigan Aerospace.

Michigan Aerospace has also proposed and been awarded a DOE Phase 2 Small Business Innovation Research (SBIR) contract to demonstrate a total system solution for wind turbine control, involving the combination of UV LIDAR, condition monitoring and decision-making software, and advanced control techniques. This work will culminate in testing of the UV-Lite LIDAR and integrated software on the CART-3 platform at NREL. We are also in discussions with a utility-scale turbine OEM regarding field testing, which would be a logical follow-on to the CART-3 testing.

A long-term test program is being proposed to enable data collection and analysis over multiple wind seasons. The test program would involve at least one utility-scale turbine platform and focus on making integrated feed-forward LIDAR control a practical solution for turbine OEMs. Various control strategies will be evaluated, including those that utilize condition monitoring data in conjunction with LIDAR atmospheric data (e.g., fault-tolerant approaches).

OptoAtmospherics has raised over \$7M in venture financing and is currently working with strategic partners to evaluate prototype LIDARs in the field starting in 2013. A production team has been hired to transition the technology from demonstration phase to production. Low-rate initial production is anticipated to start in 2014. No other company has demonstrated multi-range, volumetric measurement of wind speed, direction, temperature and density *simultaneously*, at both short and long ranges (up to 18km). This enabling technology will make an immediate and significant impact in improving turbine efficiency and lifetime, turbine performance validation, wind farm site assessment and optimization, as well as advancing grid integration and forecasting accuracy. Figure 24 shows an illustration of the short range implementation on a wind turbine. Figure 25 shows the Next Gen UV-Lite prototype. DOE funding has played a key role in moving this technology forward. The collaboration between Michigan Aerospace, OptoAtmospherics, DOE, NREL, the Colorado School of Mines, and turbine OEMs provides a unique opportunity to bring products to market sooner that improve the overall Cost of Energy for wind.

FIGURE 24 TURBINE MOUNTED LIDAR ILLUSTRATION

FIGURE 25 SHORT-RANGE UV LIDAR BETA UNIT