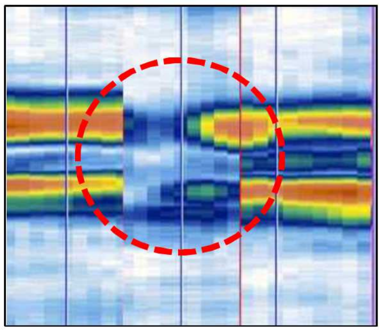
Critical, Cost-Effective Wind Blade Inspections Using Autonomous Inspection Systems

SAND2018-9339C



Dennis Roach, Ray Ely, Tom Rice, Josh Paquette

Wind Blade Reliability Center

Sandia National Labs

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Rising Need for Wind Blade Inspections

- Rapid and steady increase in wind power installation

- Critical enablers to improve market competition with other electricity sources - *Dept. of Energy Wind Vision Roadmap* identifies need for continuing declines in wind power costs (blade availability) and improved reliability

- Increase wind farm availability and lower production costs by reducing unplanned maintenance - requires broader adoption of condition monitoring systems

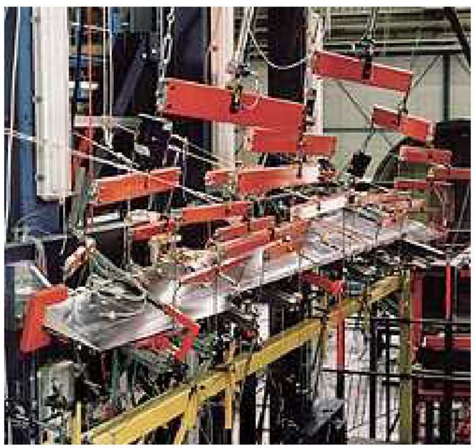
- Better understanding of harsh environments combined with uncertainties in aging phenomena and Damage Tolerance of blades

- Blade maintenance is now a major issue because: 1) the number and age of wind blades in operation continues to grow, 2) larger blades have increased demand/need for more invasive repairs (vs. replacement), 3) operational loads/environment combined with seeded flaws creates the need for in-service inspections

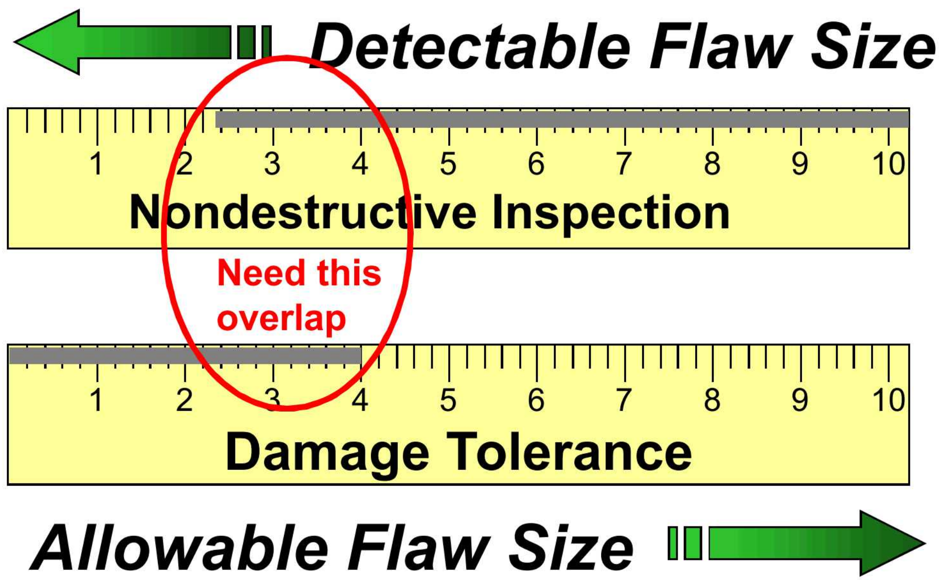
- Navigant Research estimates the cumulative global revenue for wind turbine inspection services will reach nearly $6 billion annually by 2024.

Blade Reliability Collaborative – NDI Objective

Create the ability for manufacturers to determine the quality of their product before it leaves the factory & to enhance the in-service inspection of wind blades

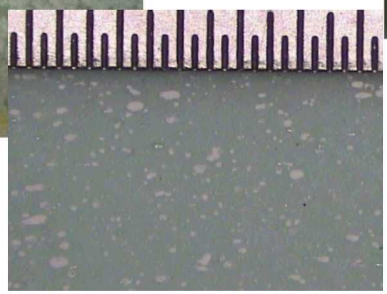


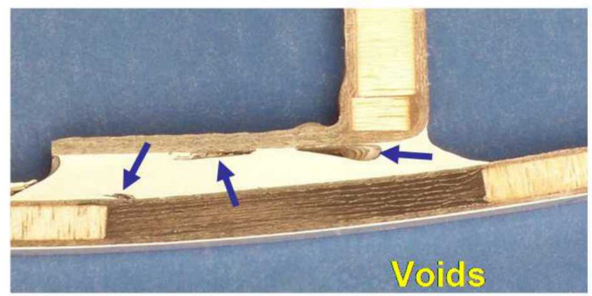
Required Relationship Between Structural Integrity and Inspection Sensitivity



Inspection Areas and Flaw Types of Interest

Flaws include: Ply Waves Delaminations, Adhesive Voids, Joint Disbonds, Snowflaking and Porosity





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In-Service Inspection of Blades Including Wind Blade Repairs

Damage Sources -
Installation, Lightning Strike, Impact, Erosion, Overstress, Fatigue, Fabrication-Seeded, Environmental

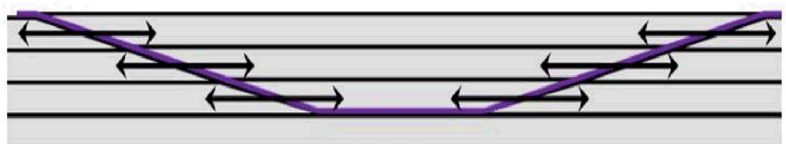
Skin Laminate Fracture

- **In-service NDI can improve blade reliability, minimize blade downtime & extend blade life**
- **Additional access & deployment challenges**
- **Post-repair inspections**

Demand for More Extensive Wind Blade Repairs Requires Pre- and Post- Repair Inspection

- Requires the means to conduct in-service inspections up-tower
- NDI must go beyond visual surface indications and produce deep, subsurface damage assessments
- NDI must be rapid to minimize blade downtime

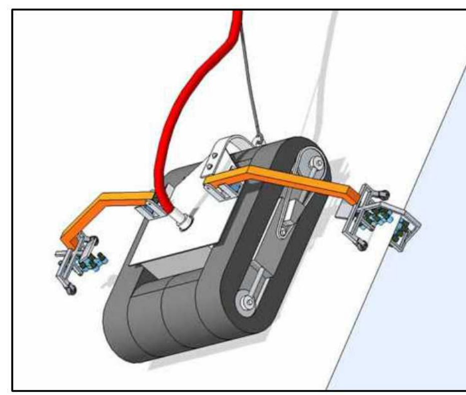
Severe Growth of Fiber Fracture



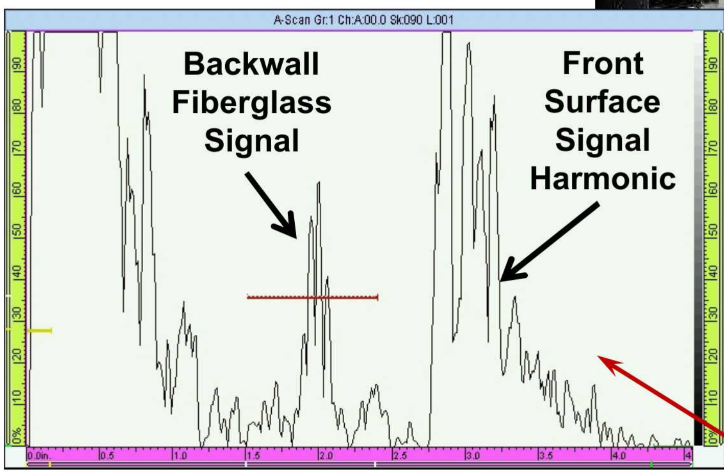
Scarfed Blade Repair Process

Lightning Strike Damage

Drone- and Robot-Deployed NDI Systems



Overcome Inspection Challenges



Want to make NDI easier, quicker, more reliable and more sensitive

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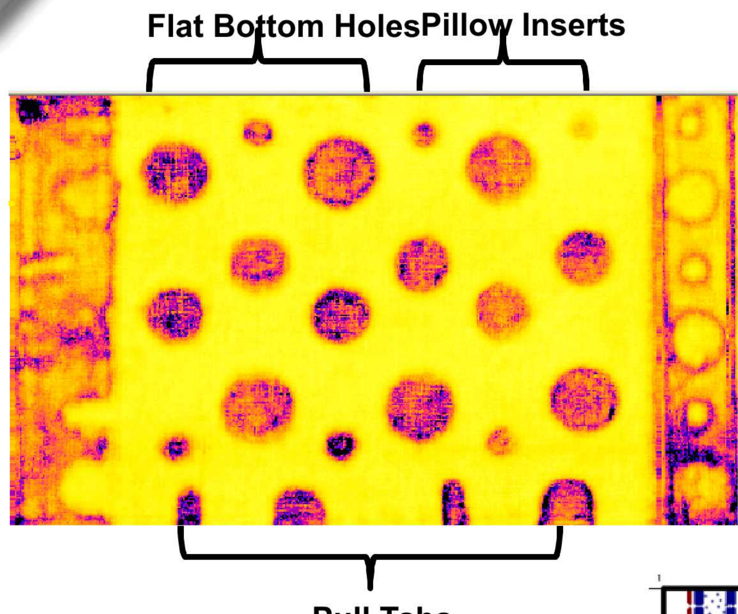
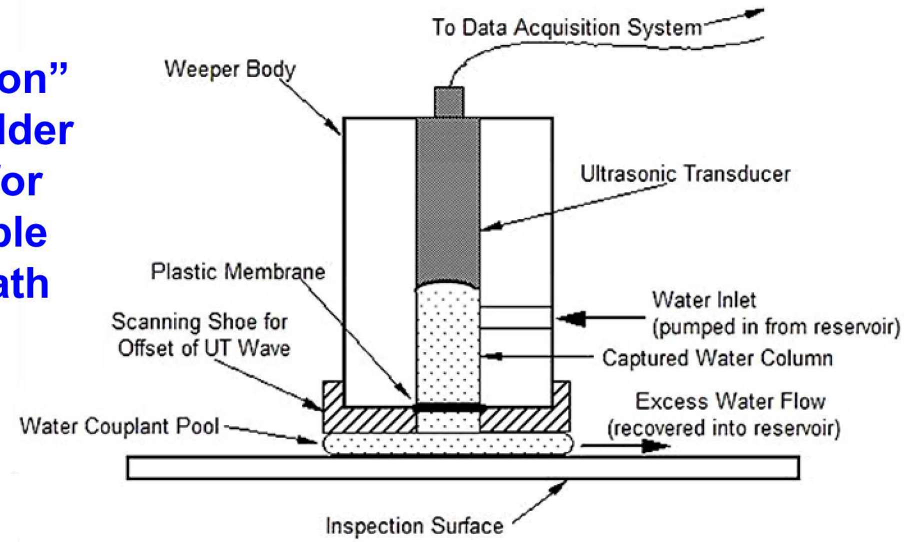
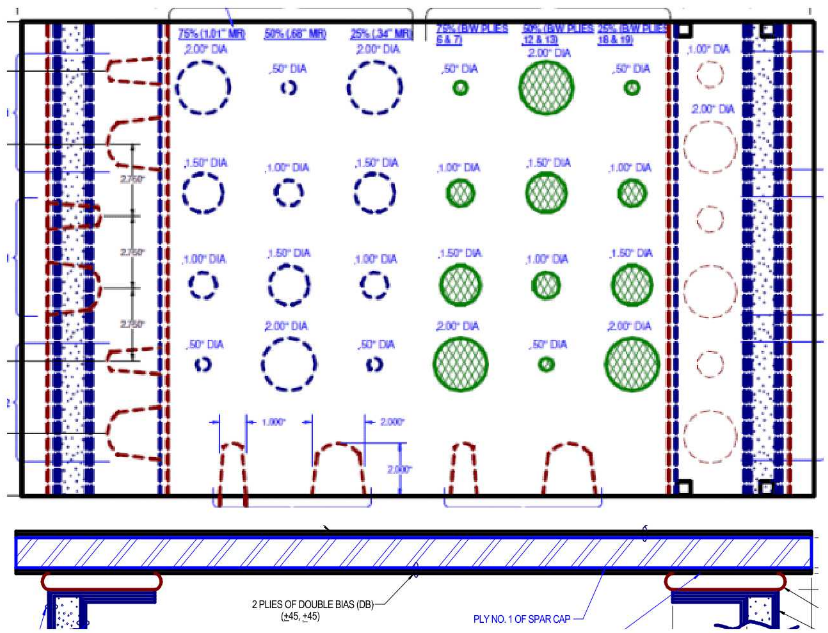
MAUS P-E UT with Focused Probe (1 MHz/2”) and Adjustable Water Path



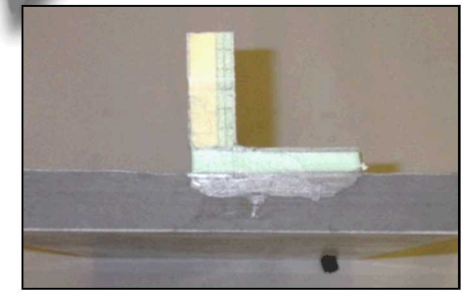
REF-STD-6-202-250-SNL-1

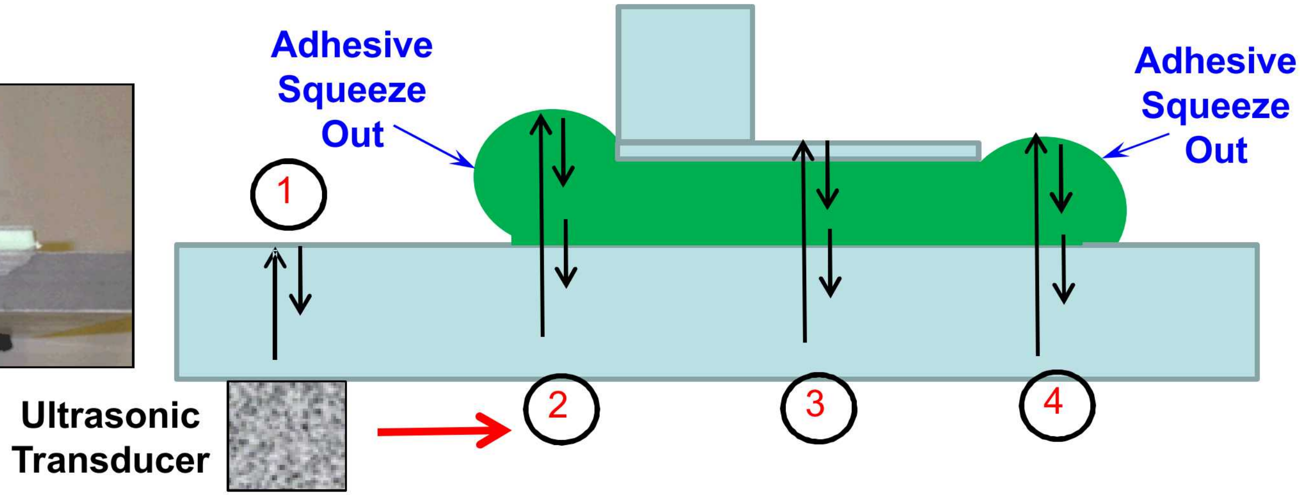
New “Immersion” Probe Holder Allows for Adjustable Water Path

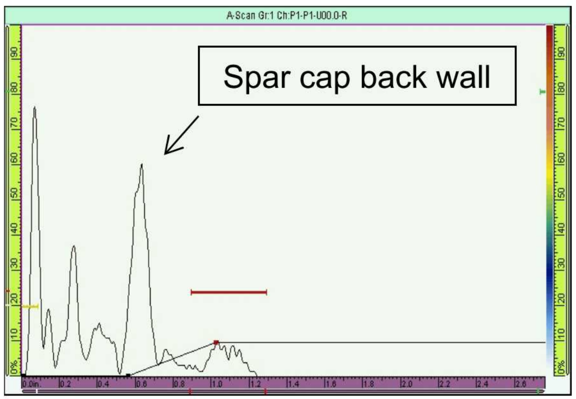




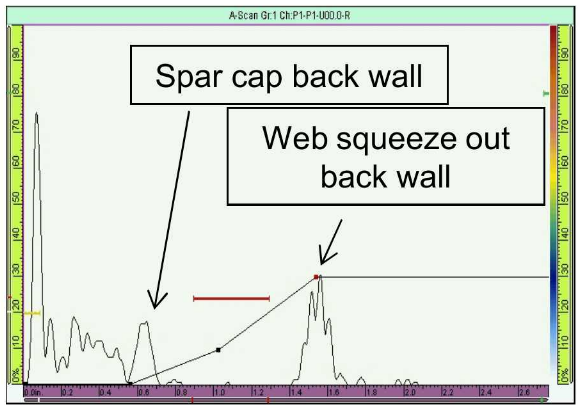
Pulse-Echo Inspection of Bond Joint



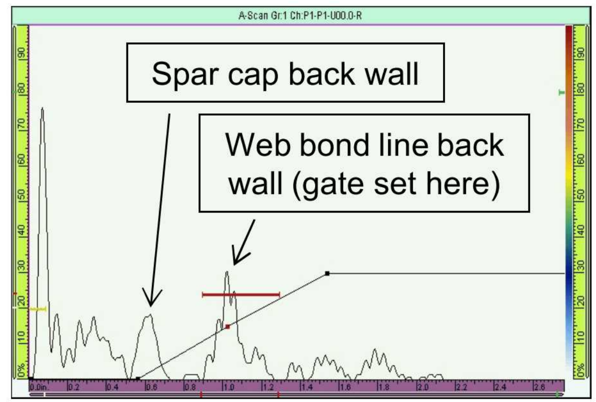




Spar Cap - 1

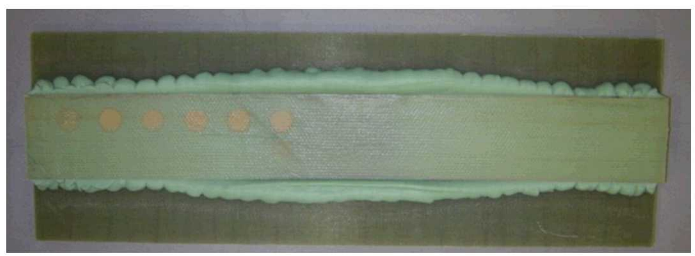


Web Squeeze Out- & 2 4



Web Bond Line- 3

A-Scan Signals



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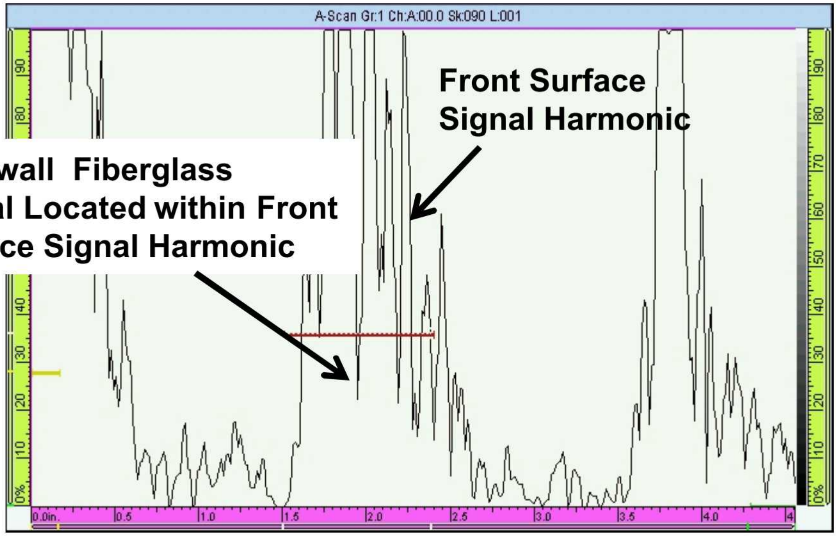
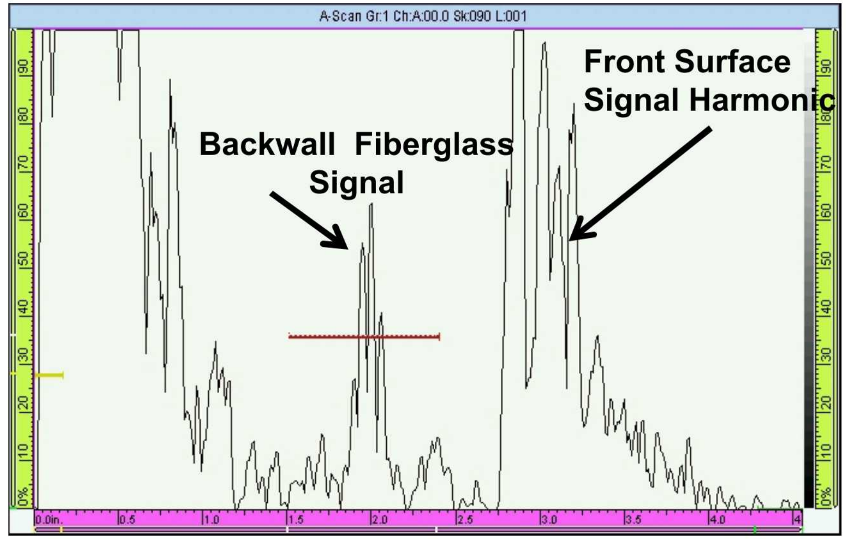
Design of Delay Lines to Avoid Signal Interference

Water Box Signal Analysis - 25mm compared to 40mm; Moves harmonic return signal outside area of interest.



25mm Delay



40mm Delay

1.5 MHz Phased Array UT Probe

Sandia has focused on a sealed couplant box that:

- **Adjusts to slight curvature in surfaces**
- **Eliminates water flow to open box**
- **Maximizes signal strength**
- **Accommodates necessary standoffs for signal clarity**
- **Easily saves scanned images for reference using a wheel encoder**

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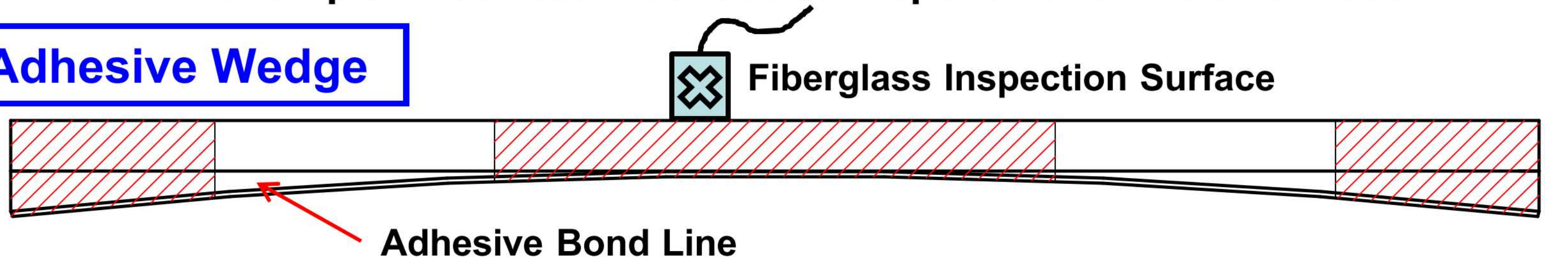
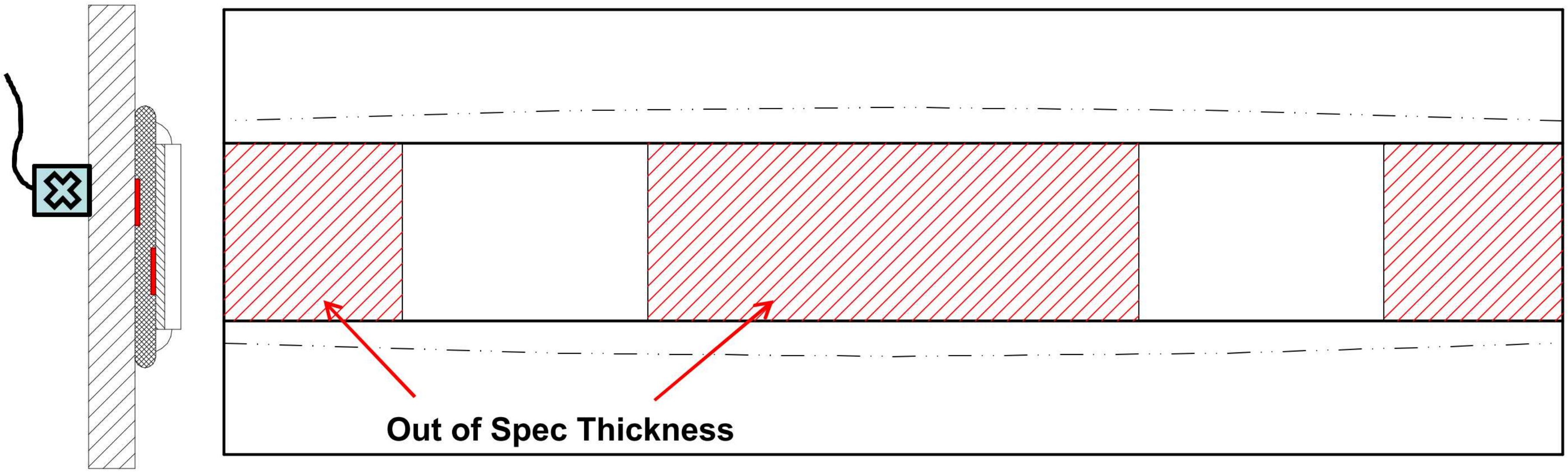
Adhesive Thickness Measurements with Phased Array UT

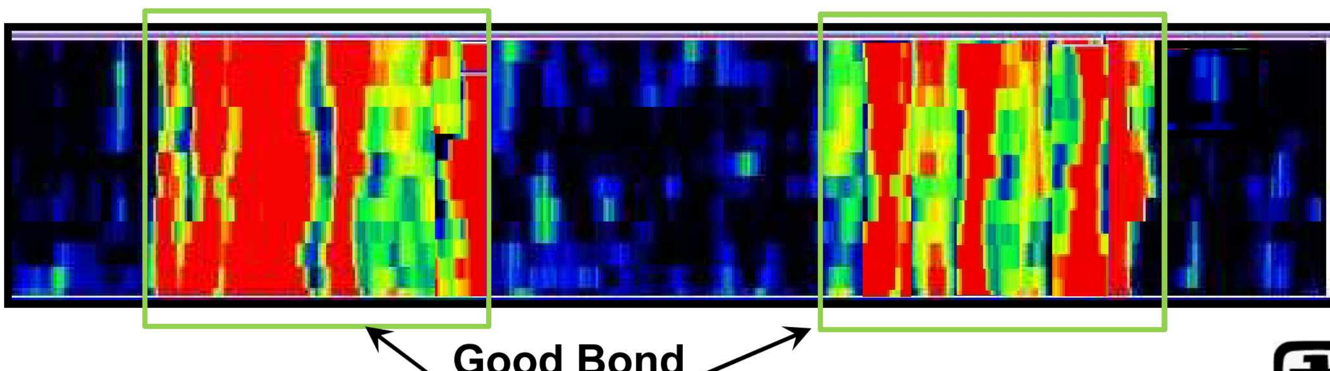
Develop and assess methods to inspect bond line thickness

Tapered Adhesive Wedge





Phased Array UT Results



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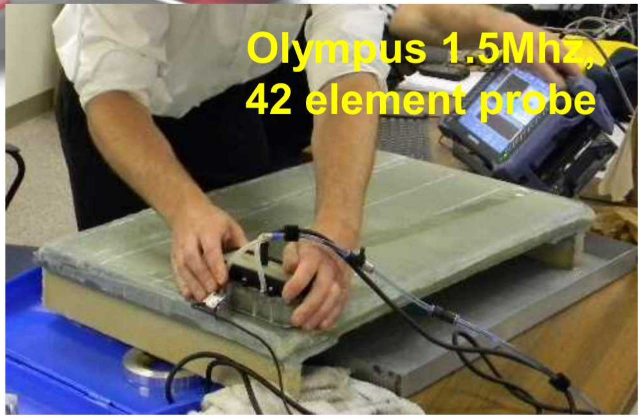
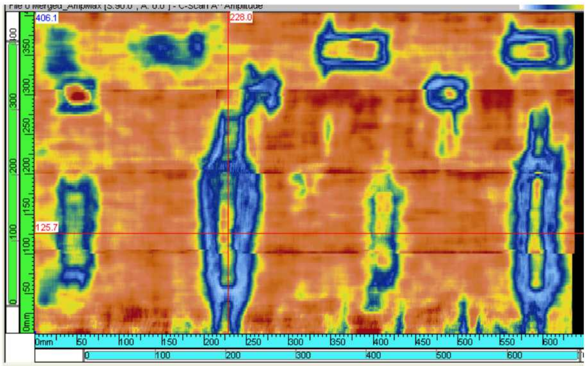
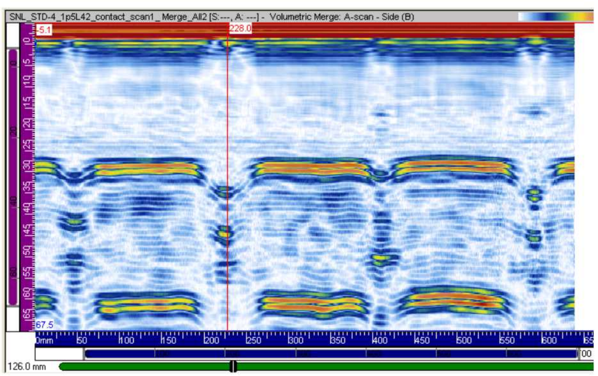
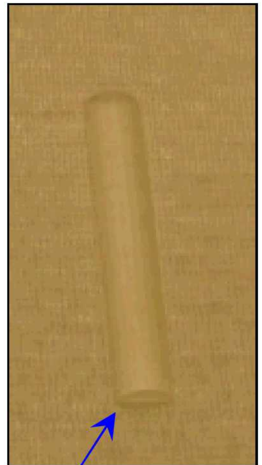
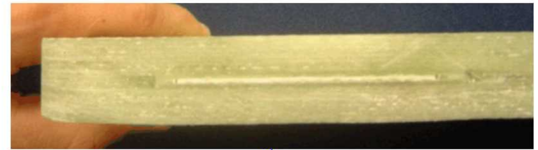
Phased Array UT – Display and Deployment







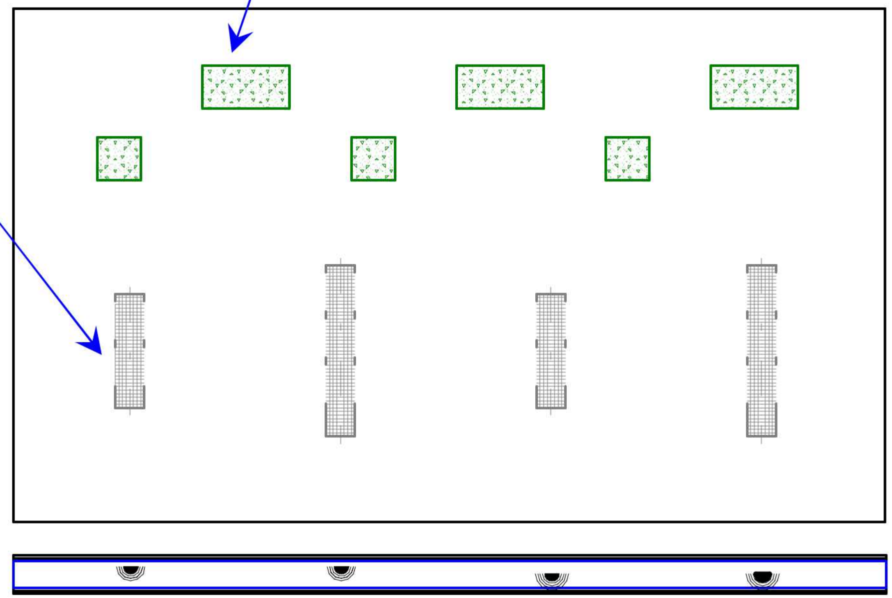




Dry Fiber Areas

REF-STD-4-135-SNL-1 (wrinkles & dry areas)

Resin Rod Induced Waves



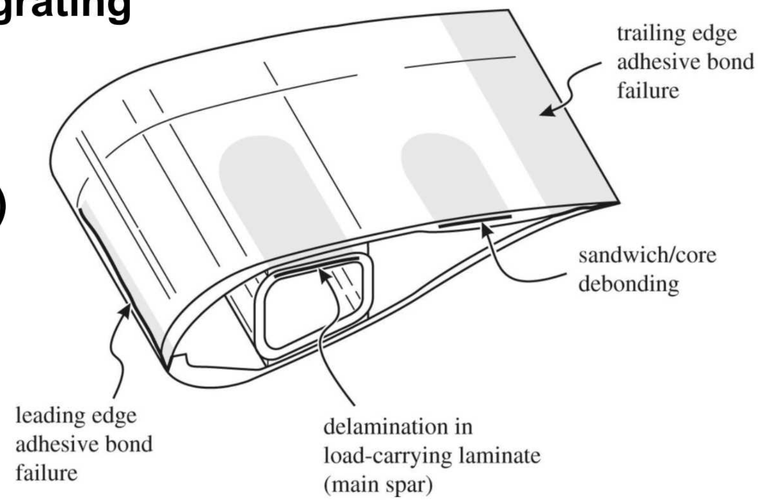
An Experiment to Assess Flaw Detection Performance in Wind Turbine Blades (POD)

Purpose

- Generate industry-wide performance curves to quantify:
  - how well current inspection techniques are able to reliably find flaws in wind turbine blades (industry baseline)
  - the degree of improvements possible through integrating more advanced NDI techniques and procedures.

Expected Results - evaluate performance attributes

1) accuracy & sensitivity (hits, misses, false calls, sizing)
2) versatility, portability, complexity, inspection time
3) produce guideline documents to improve inspections
4) introduce advanced NDI where needed

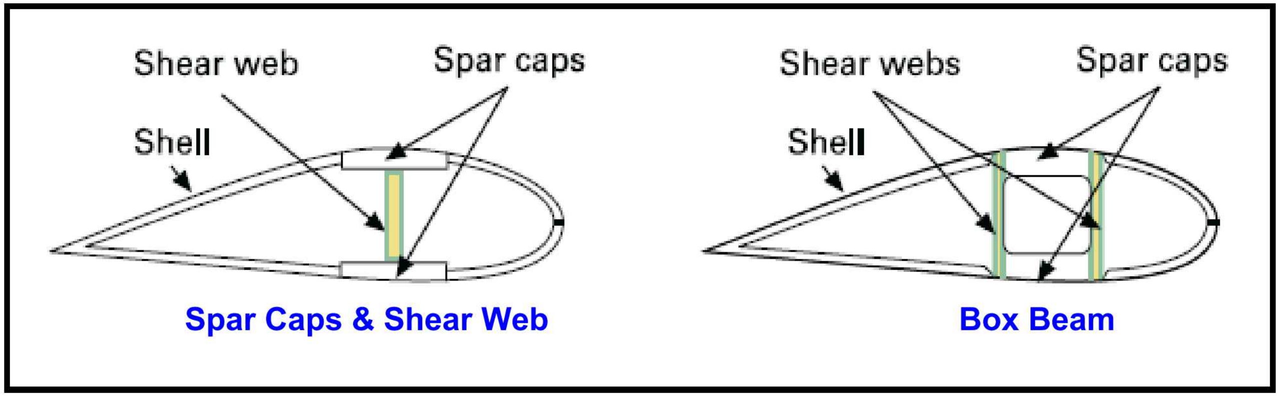


Ensure representative blade construction and materials

Implementation of Wind POD Experiment

- 11 POD specimens with spar cap and shear web geometry
- Thickness ranges from 0.45” to 2.20” thick (with adhesive bond line)
- Blind experiment: type, location and size of flaws are not know by inspector
- All panels painted with wind turbine blade paint (match inspection surface)
- Performance of NDI – hits, misses, false-calls, flaw sizing, human factors, procedures

Specimens designs applicable to various blade construction



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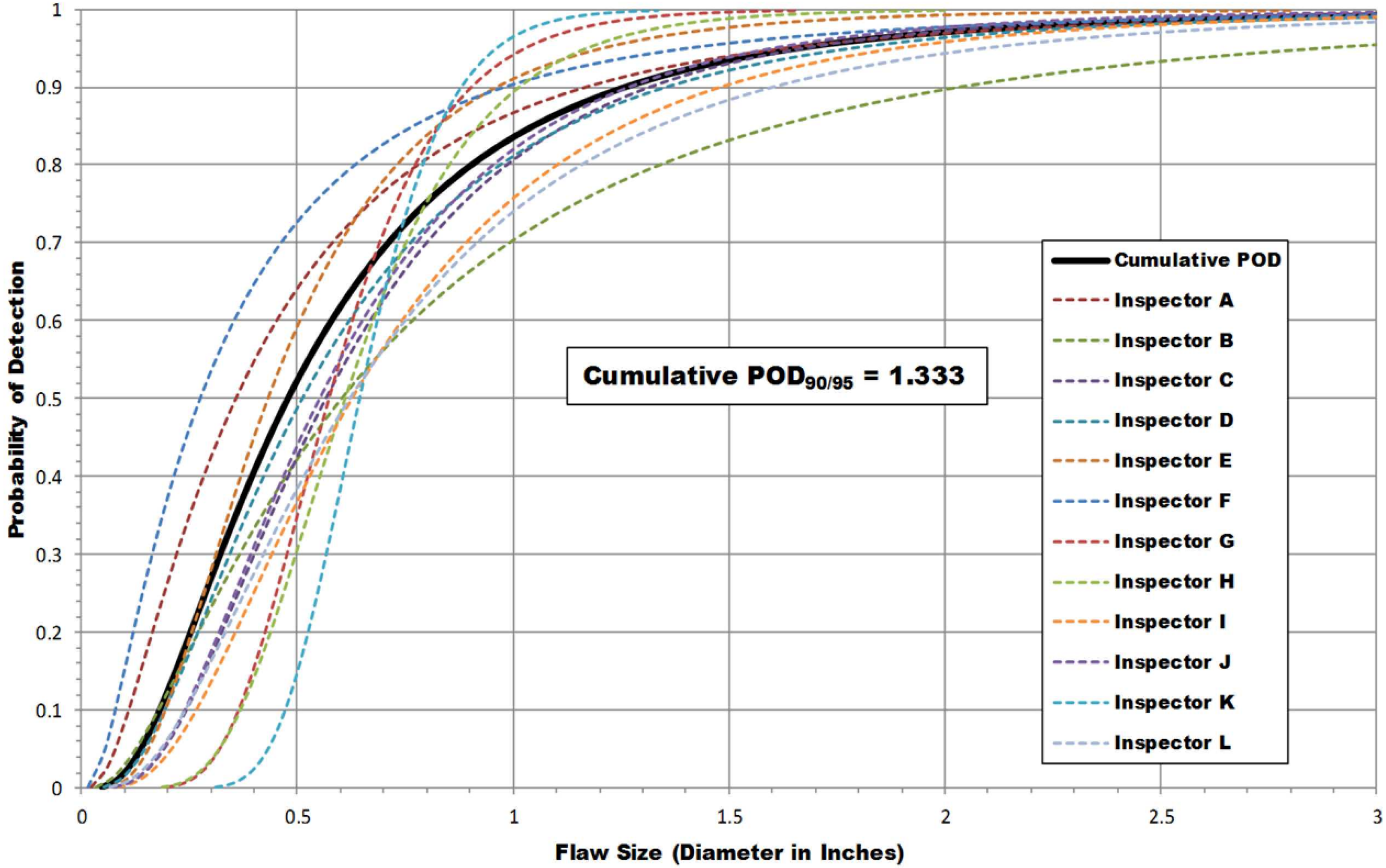
Wind Blade Flaw Detection Experiment – Individual Inspector and Cumulative POD Comparison

All Panels - Spar Cap with Shear Web and Box Spar Construction Types



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Conventional Single Element Pulse-Echo Ultrasonic Inspection Method

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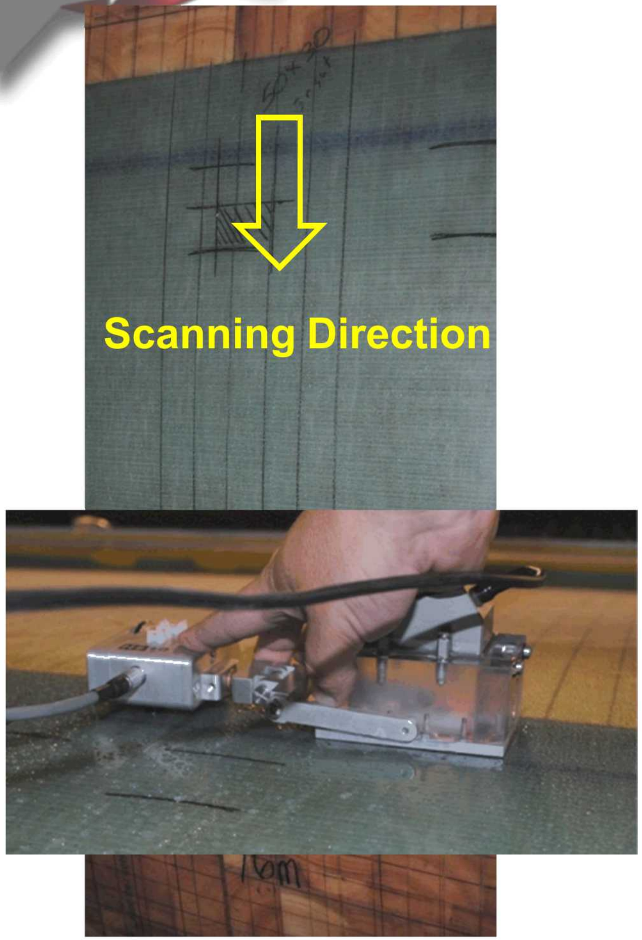
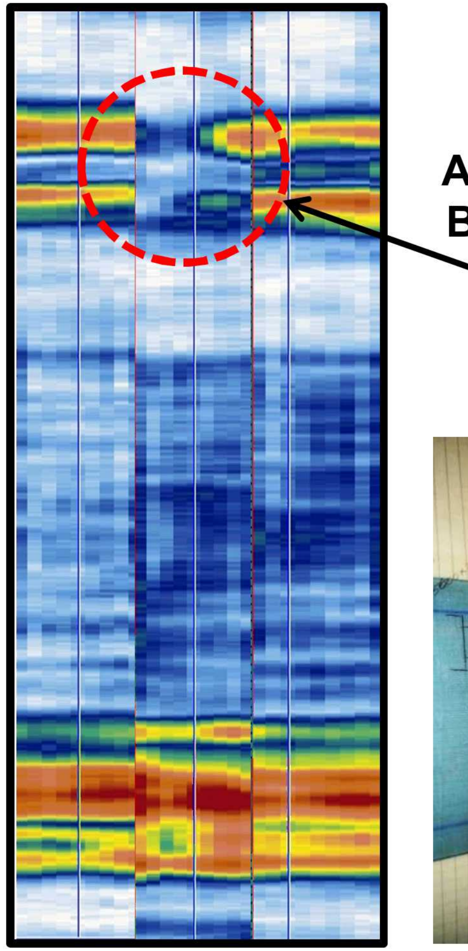
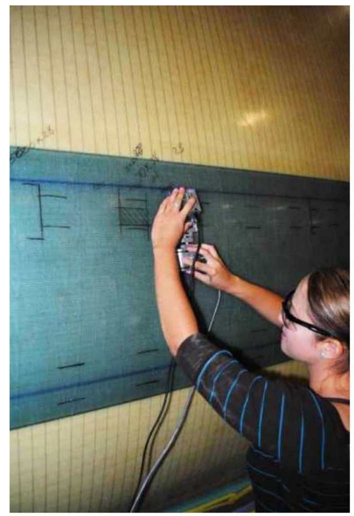
On-Blade Phased Array UT Inspections

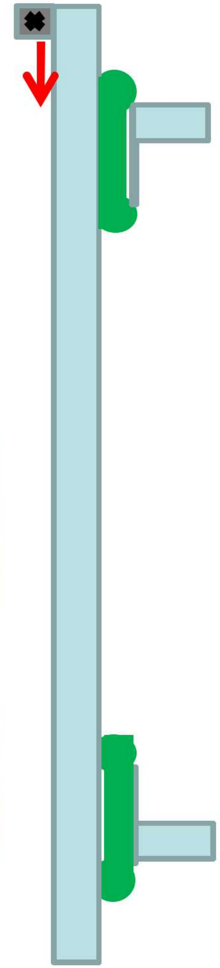


16 Meter Station on Fiberglass Spar Cap Blade



Vertical Strip C-Scan Image Showing Adhesive Void in Upper Bond Line





Spar Cap Cross Section Schematic Showing the Spar Cap, Adhesive Bond Line and Shear Webs

Sealed water box and 1.5L16 Phased Array probe was used to detect missing adhesive in bond lines

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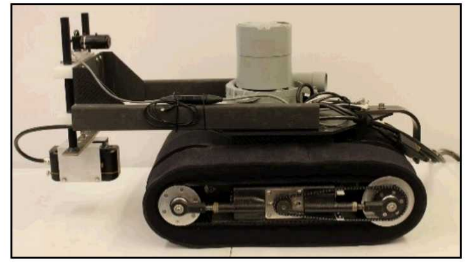
Wind Blade In-Service Inspection – Robot-Deployed NDI System



- Automated, remotely-controlled with wireless data transfer to ground station
- Includes Phased Array Ultrasonics for full-penetration damage detection
- Combined with high-fidelity visual inspection using deployed camera
- Real-time health assessment – allows for immediate repairs during a single maintenance stop and rapid return-to-service
- Benefits are escalated for off-shore applications
- Avoid more extensive repairs and even catastrophic blade failures (replacement)

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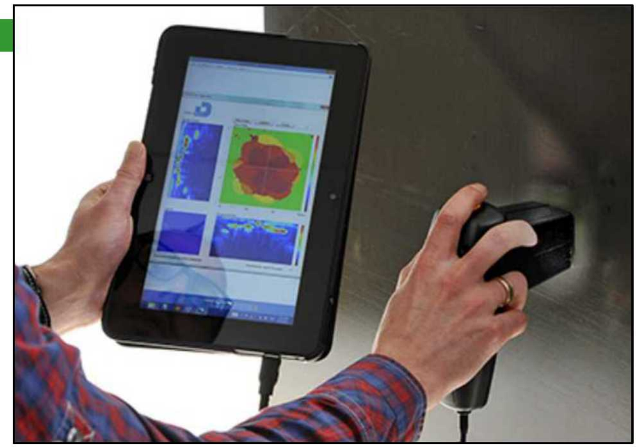
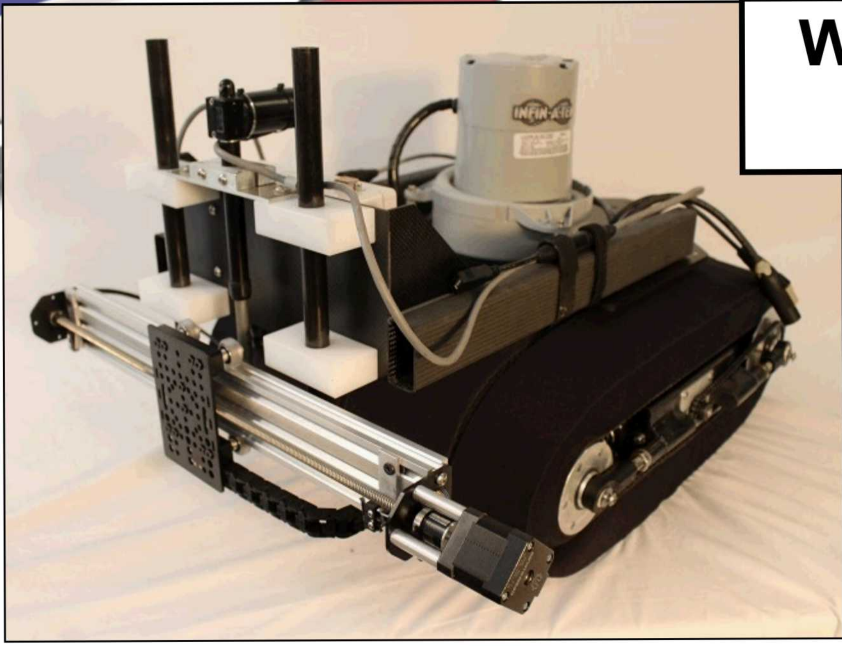


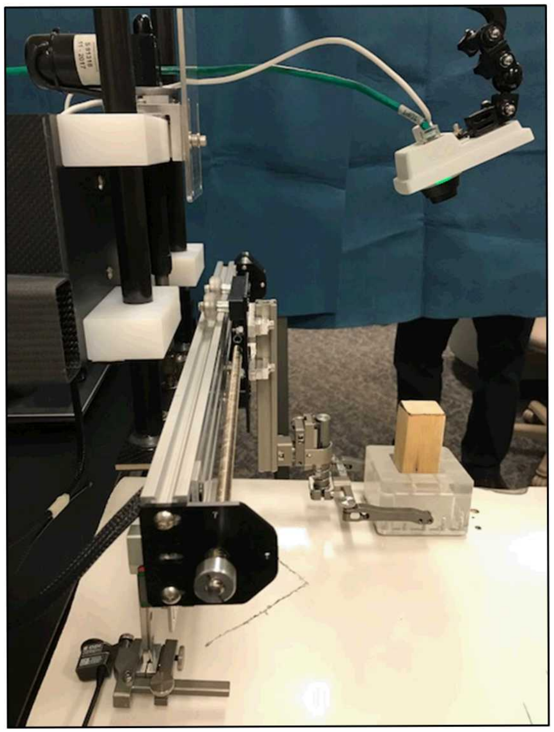
Robot with On-Board NDI System and Camera(s) for Real-Time Assessments

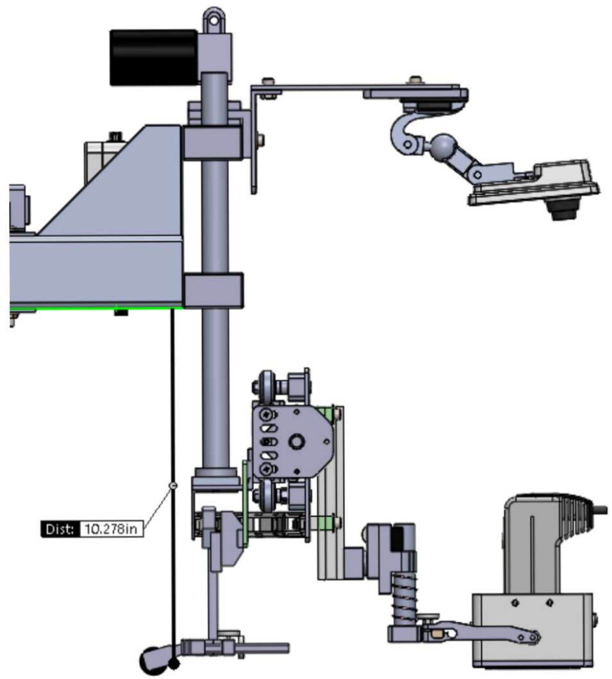
Wind Blade In-Service Inspection – Robot- & Drone-Deployed NDI Systems

- **Goal**: produce a turnkey, automated, remotely-operated inspection system capable of detecting blade damage at all depths (full-penetration) that can rapidly inspect large regions on land-based and offshore wind blades.
- **Benefits**: System will provide cost-effective, routine, surface and subsurface inspections that previously had not been performed and thus, allow blades to reach their design life; accommodate more invasive repairs (post-repair inspection) which will avoid large replacement costs.
- **Background**: U.S. DoE *Wind Vision* roadmap identifies continuing declines in wind power costs and improved reliability will improve market competition with other electricity sources; increased availability (lower production costs) can be achieved by reducing unplanned maintenance through broader deployment of condition monitoring systems.
- **Motivation**: To minimize costly downtime and repair periods and ensure successful functioning of a wind farm, it is necessary to conduct in-service inspections. As the length of blades increase and operational environments produce high stress levels in the blades, it has become increasingly important to detect the onset of damage or the propagation of fabrication defects during blade operation. Detailed NDI is also necessary to firmly establish if repairs are needed and to assess the quality of the repair (post-repair inspections). Small defects can propagate to levels of concern during blade use while fatigue loading, bird/hail impact, lightning strike, erosion and other in-service conditions can lead to new damage in the blades.

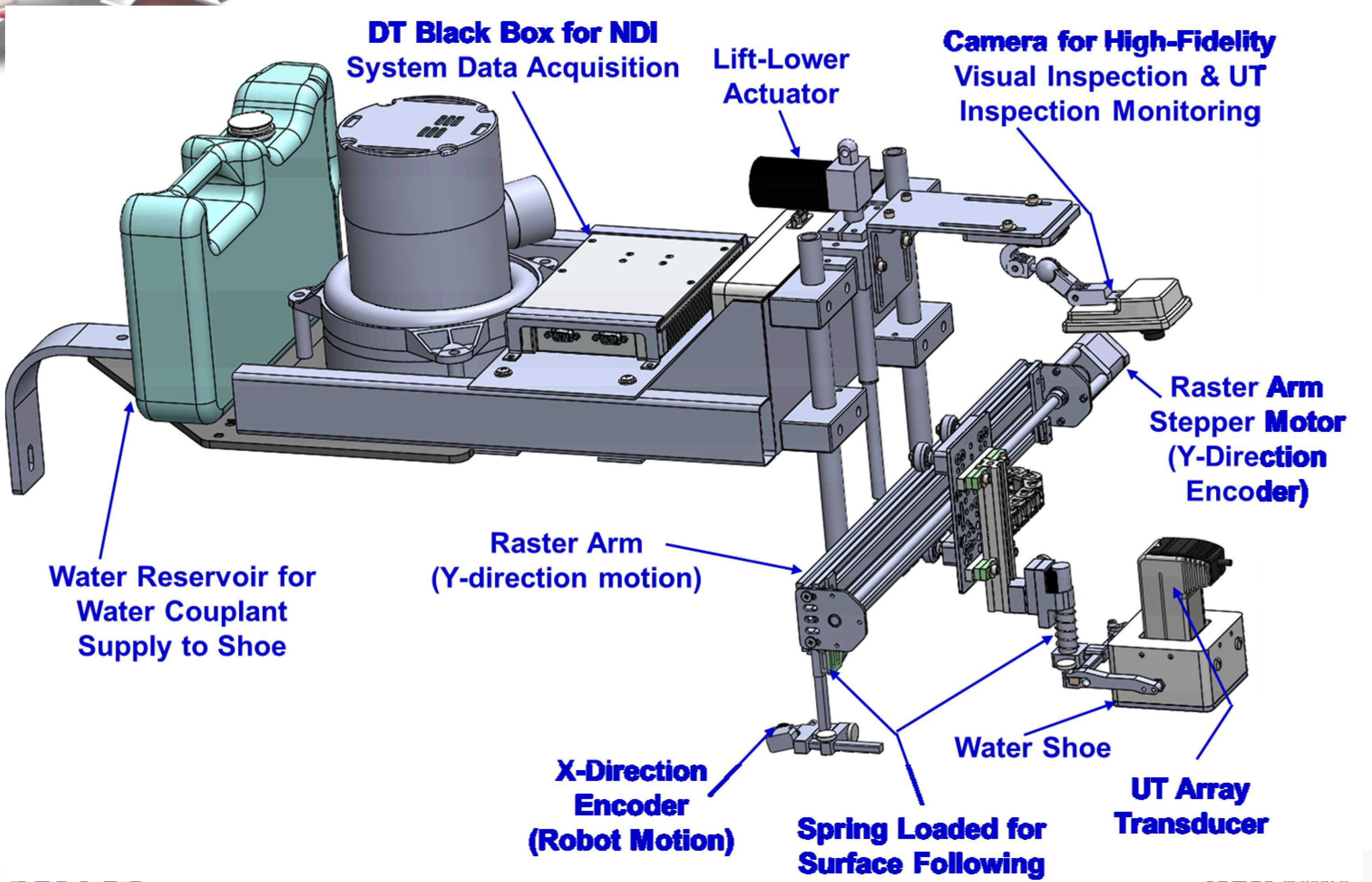
Wind Blade In-Service Inspection – Robot-Deployed NDI System







Component Integration on Robot Superstructure



Wind Blade In-Service Inspection – Robot-Deployed NDI System

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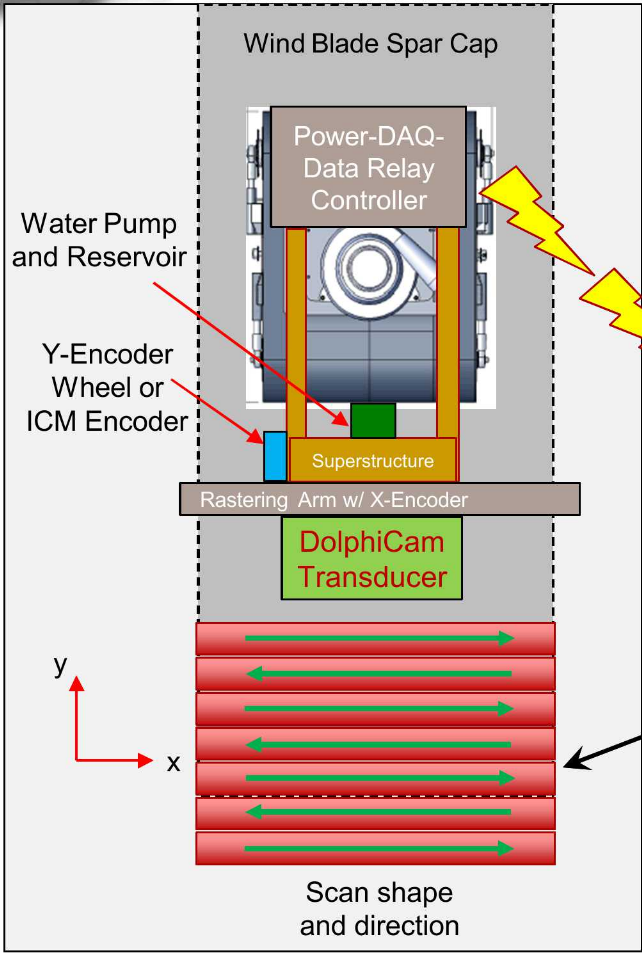
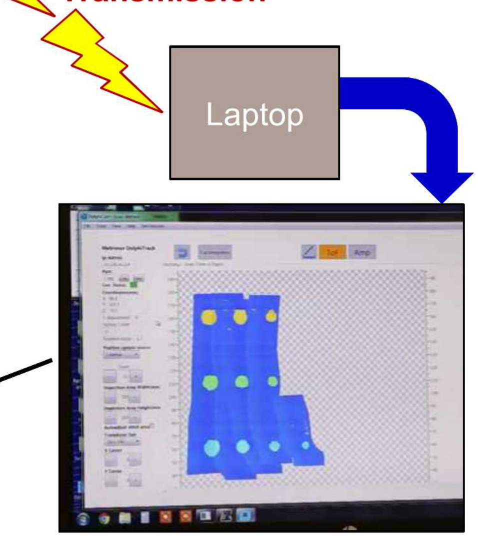
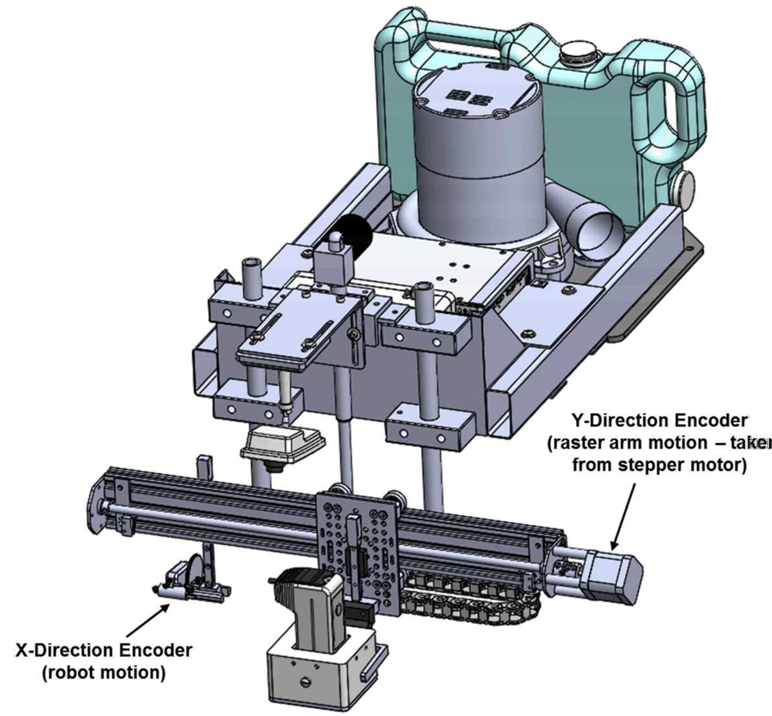


Low-Frequency Dolphi-Cam UT Imaging System with DAQ Box for Power and Real-Time Data Transfer

Real-Time Wireless Data Transmission



Inspection Image



Robot increments in small X step and then rastering arm on robot moves DolphiCam head in the Y-direction. Repeat this process to produce a 2-D C-scan.

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Wind Blade In-Service Inspection – Robot-Deployed NDI System

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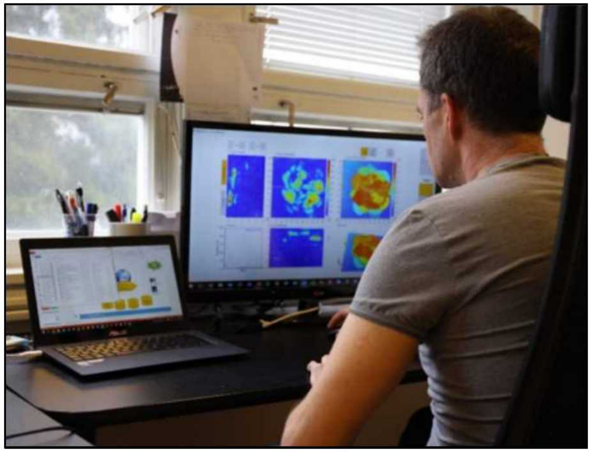
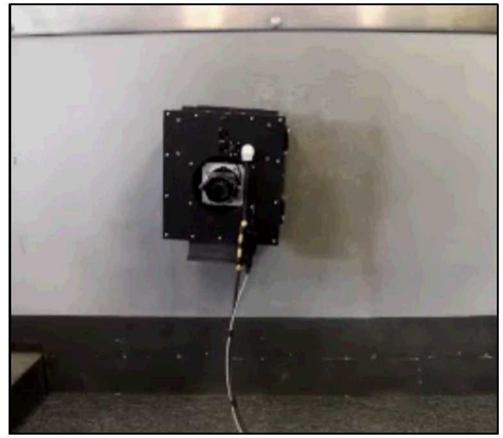
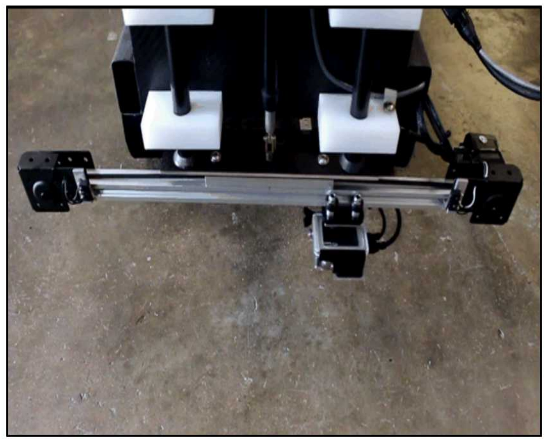


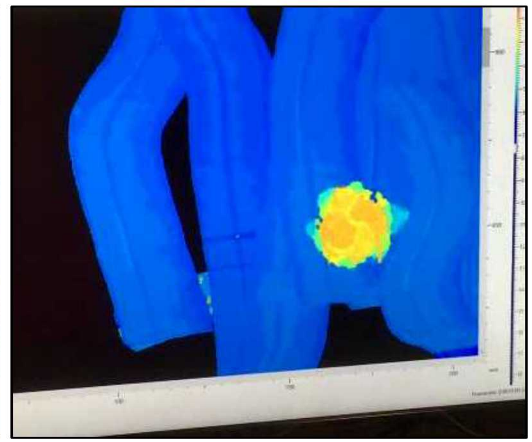
Ground Workstation – Data Acquisition & Analysis Plus Control of Robot



Robot Crawling on Vertical Surface



Raster Scan of Area



C-Scan Inspection Image

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ON-GROUND ← → ON-BLADE

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Wind Blade In-Service Inspection – Robot-Deployed NDI System

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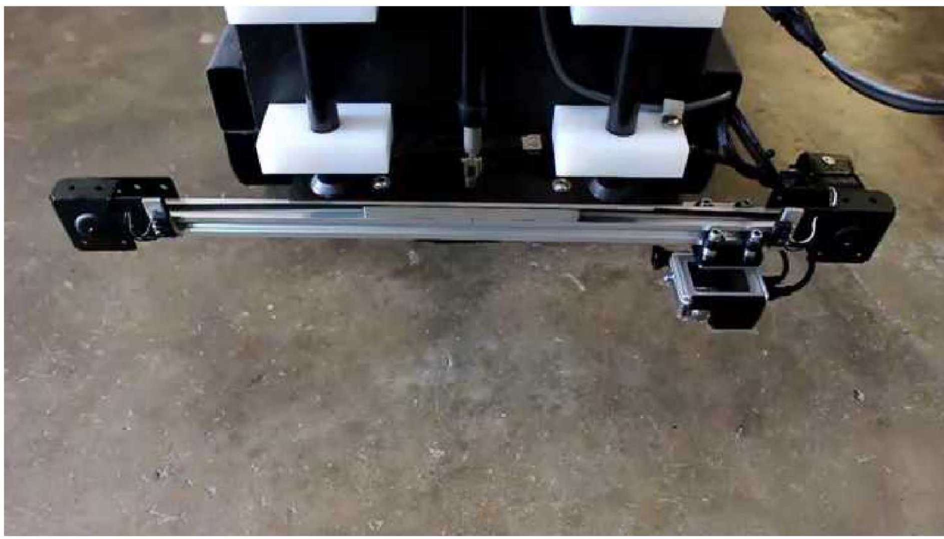
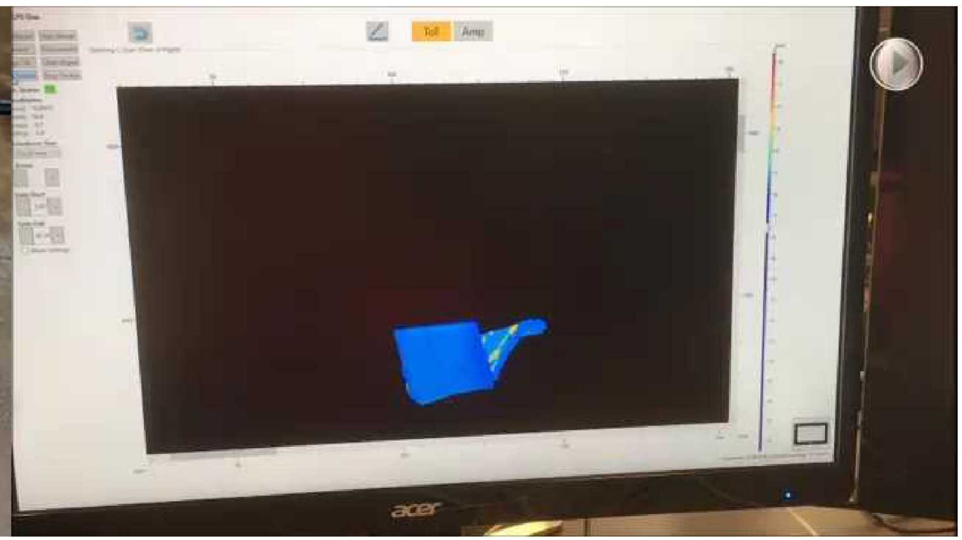
Robot Crawling on Vertical Surface

Raster Scan of Area to Produce C-Scan Inspection Image





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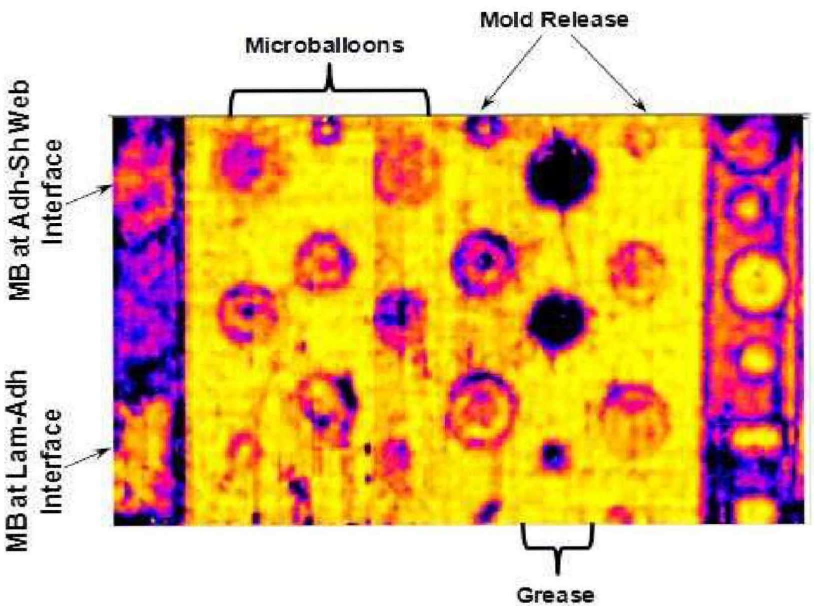
Robot-Deployed NDI System – Initial System Validation Testing



Wind Blade In-Service Inspection – Drone-Deployed NDI System

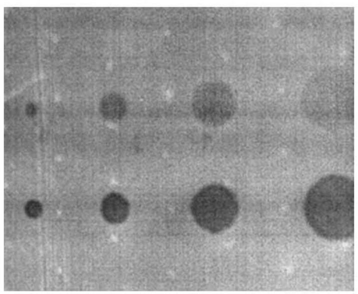
Wind Blade In-Service Inspection – Drone-Deployed NDI System

SKYSPECS

Thermography Inspection of Subsurface Flaws

Flir IR Camera

(320 X 256 pixels)

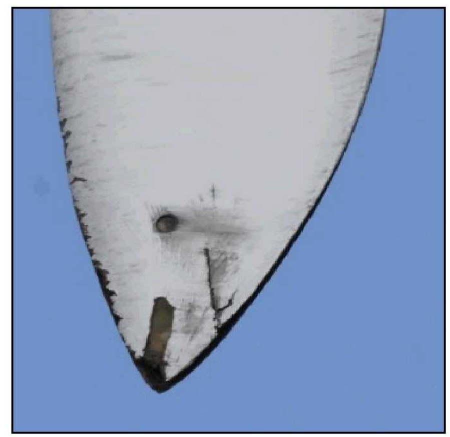


LiDAR and GPS Sensors & Computer for Automated Drone Controls

LiPo Batteries

Visual Inspection of Surface Flaws

Digital Camera



Wind Blade In-Service Inspection – Drone-Deployed NDI System

SKYSPECS

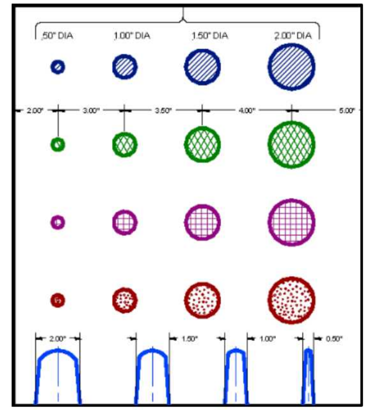
Thermal Wave Imaging

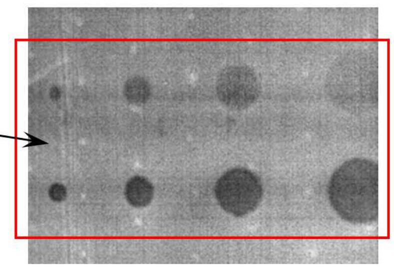
Solar Radiation Thermography

Heating: Blades Facing Sun

Cooling: Blades Facing Away from Sun

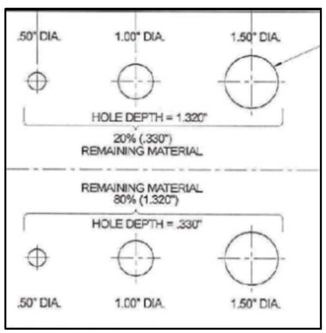
Foam Core with Fiberglass Skin



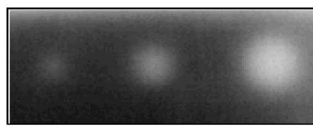


Heating Duration: 60s

Thick Fiberglass Spar Cap



.330" Deep Flaws Clearly Visible



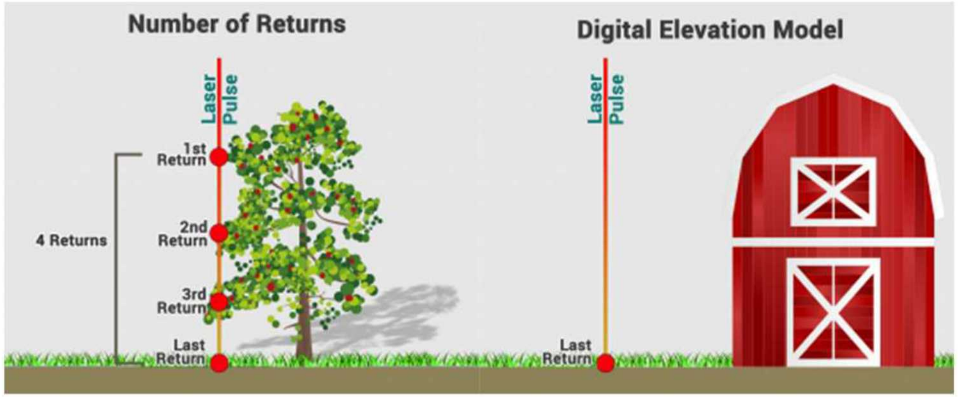
.660" Deep Flaws Barely Visible

Heating Duration: 120s

IR Images of Engineered Damage

Wind Blade In-Service Inspection – Drone-Deployed LiDAR Sensors

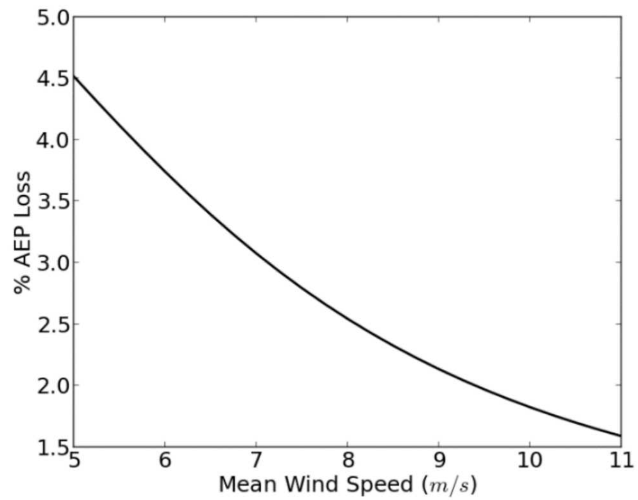
Leddar M16 LiDAR Sensor



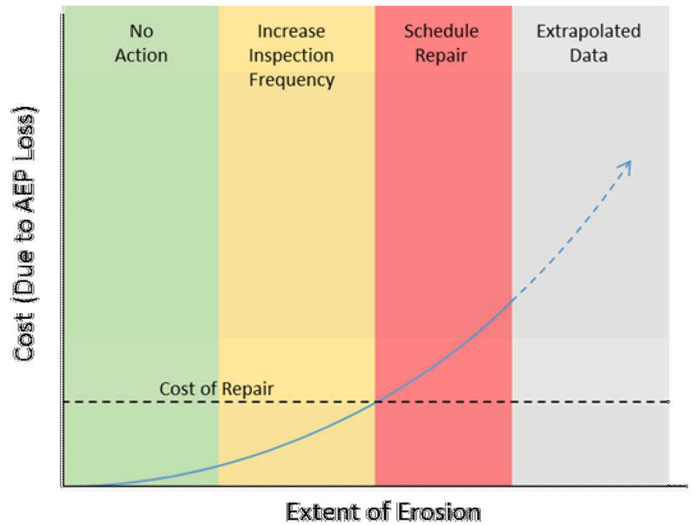
Example of Multiple and Single LiDAR Returns
(http://gisgeography.com/lidar-light-detection-and-ranging)

Using LiDAR sensors to measure leading edge erosion, predict AEP loss, and provide guidance on performing erosion repairs

Erosion Example



Decrease in Annual Energy Production vs. Mean Wind Speed
(Maniaci, D., "Leading Edge Erosion: Measurement and Modeling Campaigns," Sandia Report, SAND2016-8898, August 2016.)



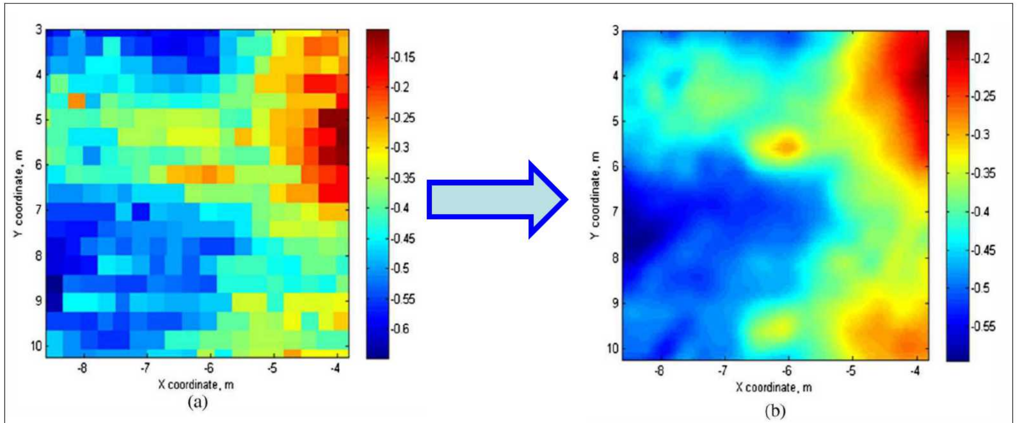
Notional Example of LiDAR-Based Decision Making

Wind Blade In-Service Inspection – Drone-Deployed LiDAR and IR Camera Integration

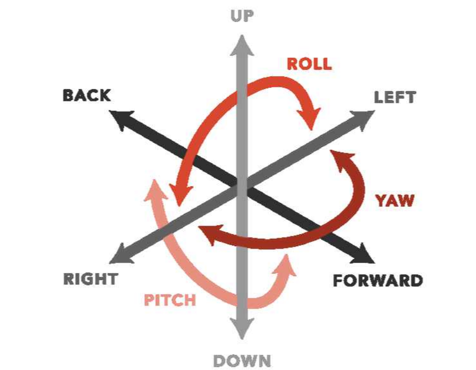
Thermal Wave Imaging

ETV

Use NASA's SuperResolution Algorithm to Process Data



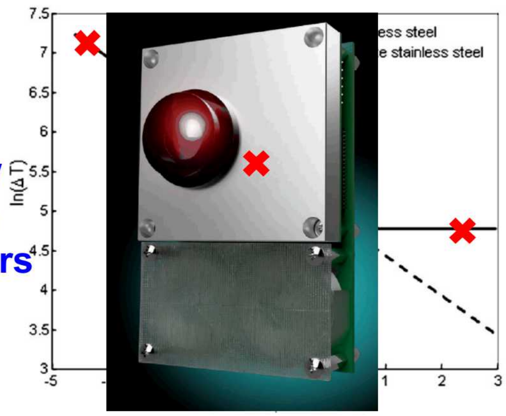
Increase LiDAR Resolution



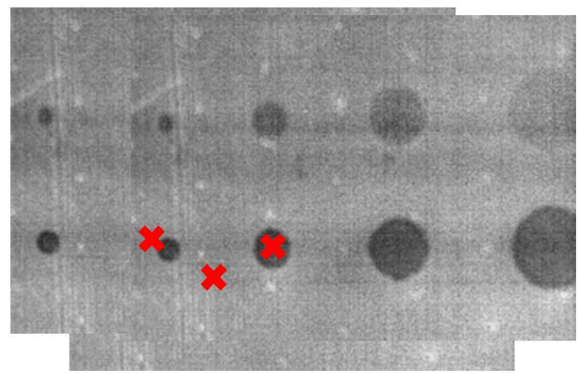
Measure Relative Changes in 6 DOF state vector

Enables the drone to track relative position and orientation changes in order to measure IR data at an area of interest over time

Enables the use of low weight, low resolution solid-state LiDAR sensors



Temperature vs. Time history is needed to use Thermal Wave Imaging's TSR algorithm



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Wind Blade In-Service Inspection – Automated Damage Classification

- The goal is to produce an automated Damage Assessment and Maintenance Plan with actionable recommendations for Owner/Operators

Establish Damage Severity Levels

LE erosion has penetrated into the blade structure exposing the underlying laminate of the leading edge.

LE erosion has removed the protective gelcoat and begun to penetrate into the bond and had exposed the underlying laminate of the leading edge.

LE erosion has removed the protective gelcoat and begun to minimally penetrate into the bond.

LE erosion has begun and appears to be superficially limited to the outer protective gelcoat.

The leading edge shows beginning signs of LE erosion and is limited to the outermost, superficial layers of protective gelcoat.

Use Image Augmentation Techniques to Increase the Size of the Training Set

Train and Validate Damage Classification Neural Network

Next Phase: Add NDI methods to develop a more advanced damage classification system

Challenge: Acquiring enough images of damage to create a strong training set

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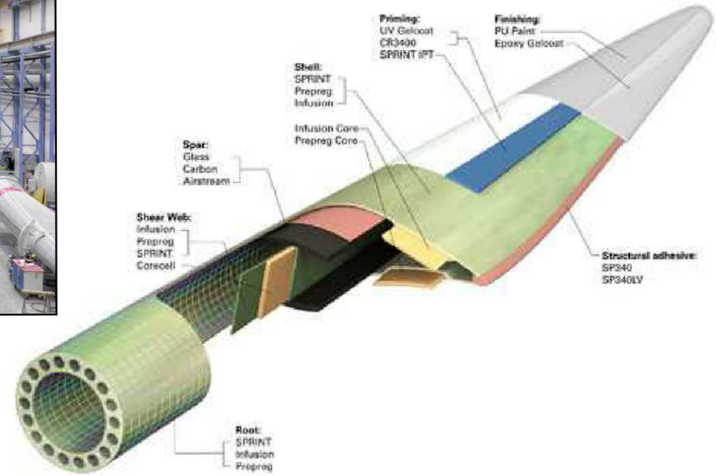
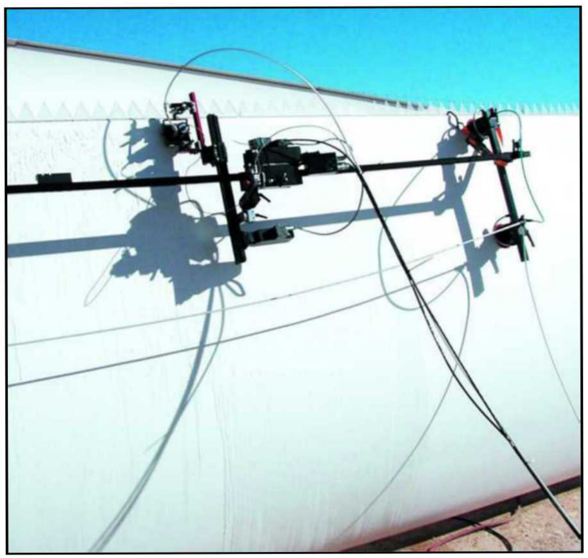
Wind Blade Flaw Detection Needs – Role of Inspection in Production and Operation

- **Need for accurate NDI** becomes more important as the cost per blade, and lost revenue from downtime, grows
- **Many Inspection Challenges** - very thick and attentive spar cap structures, porous bond lines, varying core material & different manuf./in-service defects
- **NDI Practices Vary Widely** – differing levels of rigor & methods used
- **In-Service Inspection Needs** - damage from transportation, installation, stress, erosion, impact, lightning strike, and fluid ingress
- **In-Service Inspection Considerations** - NDI fidelity beyond what can be provided by visual methods is required; time, cost, & sensitivity needs (minimize production, maintenance and operation costs)
- **Sandia Labs NDI Evolution** – WBFDE (POD) quantitatively assessed performance of NDI to allow for optimum deployment of more sophisticated inspection methods; there are sensitive & rapid NDI options available - automation
- Results can produce **improvements** in both **quality assurance measures during blade production** and **damage detection during operation** in the field - improve sensitivity, accuracy, repeatability & speed of inspection coverage
- Detection of fabrication defects helps enhance plant reliability while improved inspection of operating blades can result in efficient blade maintenance - **increase blade life; facilitate repairs before critical damage levels are reached and minimize turbine downtime**





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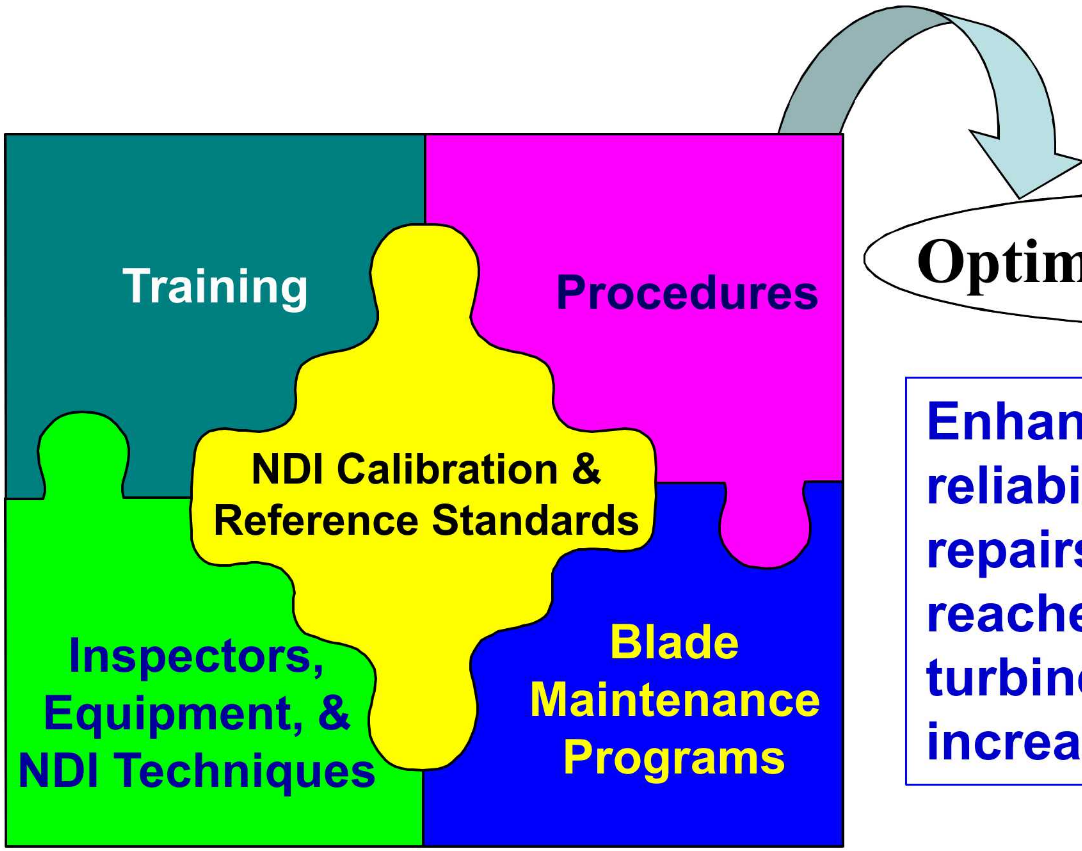
Program Thrusts to Improve Wind NDI

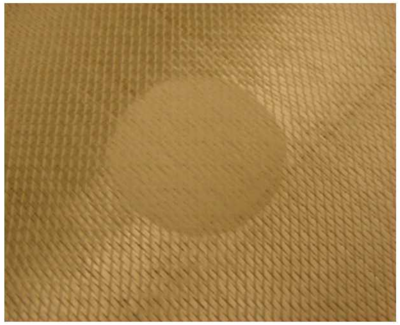
- Use of NDI reference standards to form sound basis of comparison & ensure proper equipment set-up
- Use of material property & calibration curves (attenuation, velocity)
- Human factors – adjust procedures
- Improved flaw detection: Hybrid inspection approach - stack multiple methods which address array of flaw types (data fusion)



Optimized Inspections

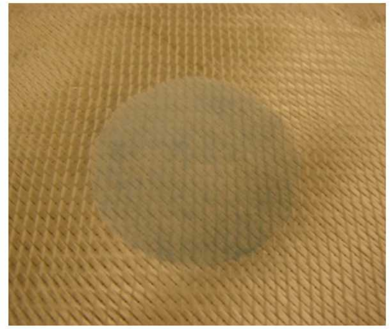
Enhance factory reliability, facilitate repairs before $a_{critical}$ is reached, minimize turbine downtime & increase blade lifetime

Different Flaw Types Engineered into NDI Performance Assessment Specimens

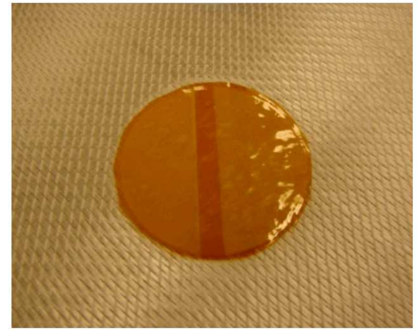


Glass Beads

Grease



Mold Release

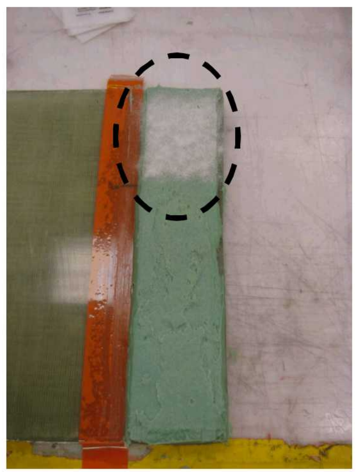


Pillow Insert

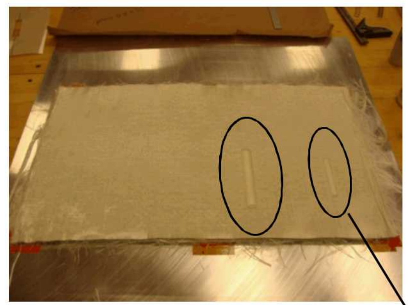
Materials inserted into multiple layers

Voids in bond joint

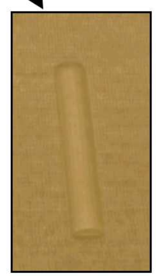
Pull tabs in bond joint

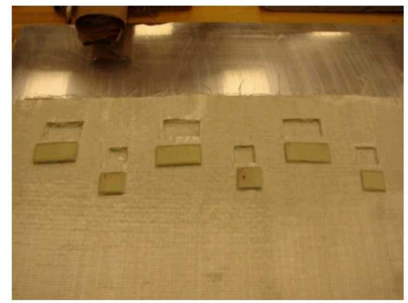


Glass beads In bond joint



Waviness produced by pre-cured resin rods

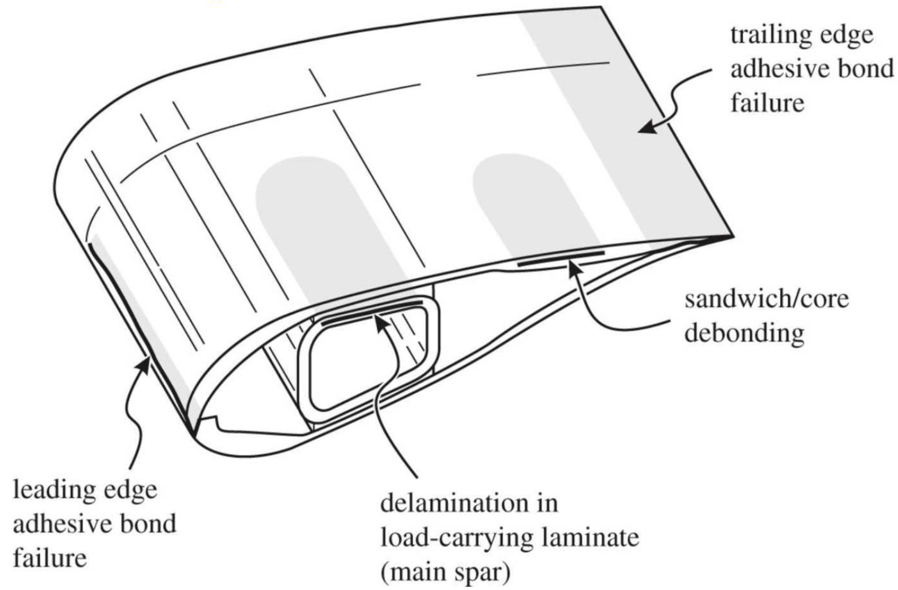




Dry fabric areas

Wind Blade NDI Probability of Detection Experiment

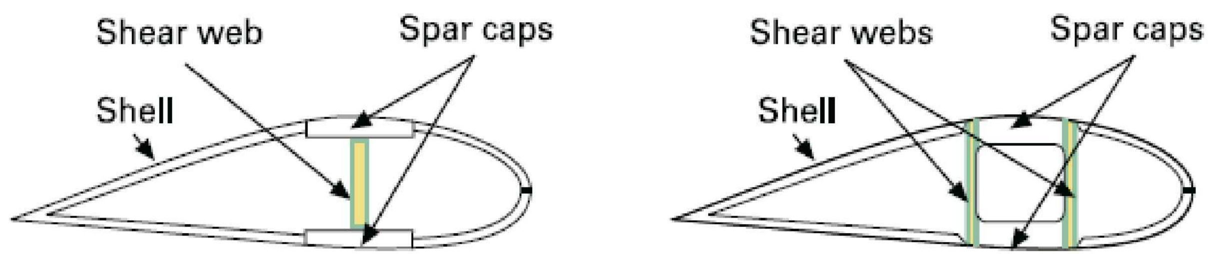
- Blind experiment: type, location and size of flaws are not know by inspector
- Statistically relevant flaw distribution – Probability of Detection (POD)
- Used to analytically determine the performance of NDI techniques – hits, misses, false-calls, flaw sizing, human factors, procedures



Experimental Design Parameters

- Representative design and manufacturing
- Various parts of blade such as spar cap, bonded joints, leading and trailing edge
- Statistically valid POD (number, size of flaws and inspection area)
- Random flaw location
- Maximum of two days to perform experiment
- Deployment

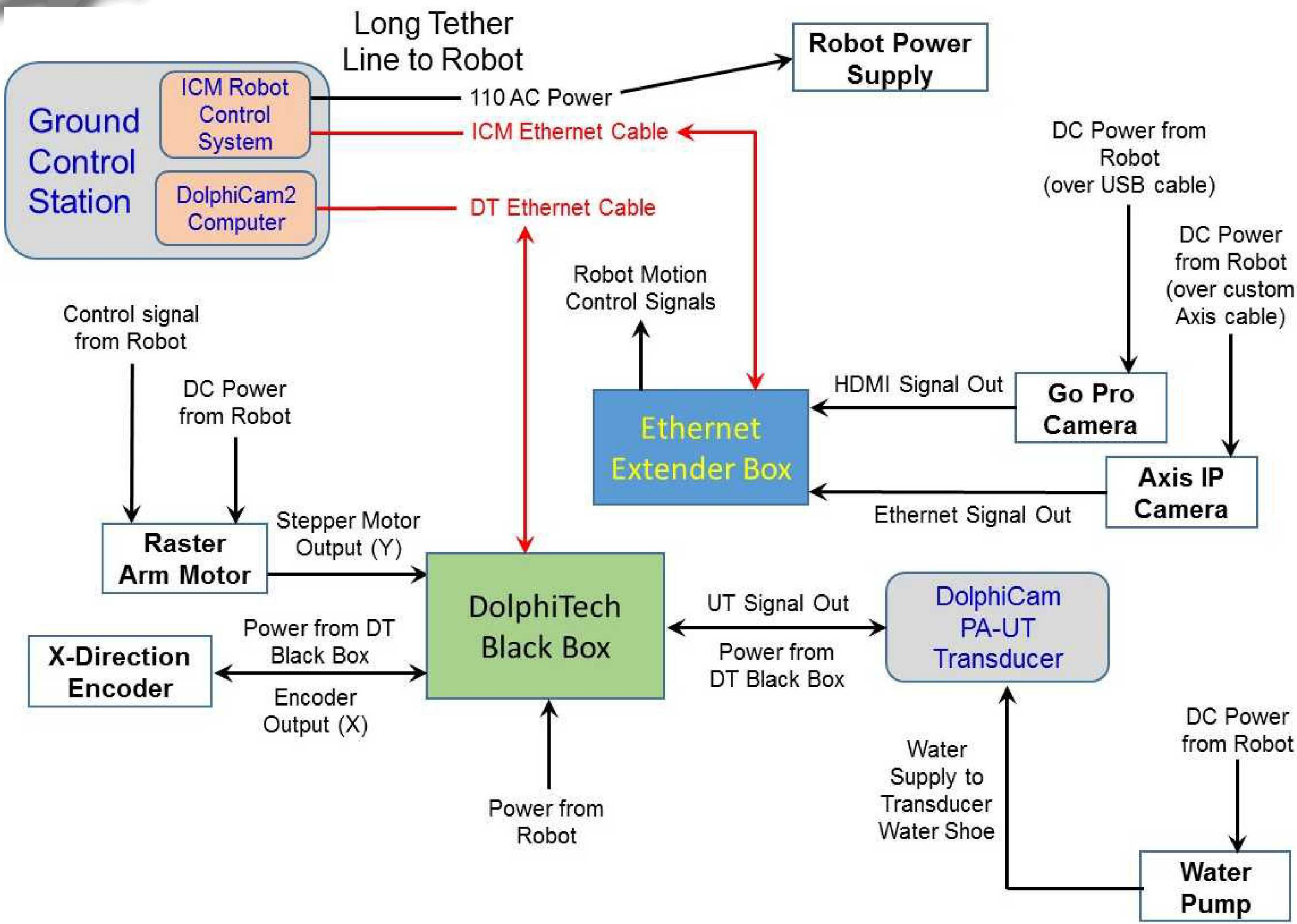
Specimens designs applicable to various blade construction



Spar Caps & Shear Web

Box Beam

Robot-Deployed NDI System – Schematic of Power, Controls and Data Transfer



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Wind Blade In-Service Inspection – Drone-Deployed NDI System

- **Through Sandia's New Mexico Small Business Assistance (NMSBA) program, we partnered with Emerging Technology Ventures to develop a plan for integrating NDI sensors with aerodynamics modeling and machine learning**
- **The goal is to produce an automated Damage Assessment and Maintenance Plan with actionable recommendations for Owner/Operators**