A computer-based inspection method for determining surface flaws of wind turbine

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Personal background

Department of Industrial and Manufacturing Systems Engineering

- **Education**
  - Ph.D. in progress in Wind Energy Science, Engineering, and Policy & minor in Statistics
  - M.S. in Industrial Engineering
  - B.S. in Mathematics, B.E. in Automation

- **Professional experience**
  - System Engineer at Shanghai Institute of Process Automation Instrumentation
  - Project Engineer at ABB
  - Intern with Exelon Wind

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John Jackman  
Associate Professor  
Dept. of Industrial and Manufacturing Systems Engineering  
Uncertainty in Systems

William Meeker  
Distinguished professor  
Dept. of Statistics  
Industrial statistics, reliability, statistical computing

Frank Peters  
Associate Professor  
Dept. of Industrial and Manufacturing Systems Engineering  
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Associate Professor,  
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NDE, Composites design and inspection

Song Zhang  
Assistant Professor  
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Machine and computer vision, virtual reality, human-computer interaction

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Committee Member  
Committee Member  
Committee Member

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The primary objective of this research is to investigate whether wind turbine blade surface images with known cracks can be detected and if so, how much of the crack can be captured and identified with computer-based visual inspection.
• Importance of wind turbine blade skin health inspection
  – Prevent early failure
    • Blades ranked No.4 (Hahn, 2006)
    • Repair duration ranked No. 3 (Hahn, 2006)
  – Reduce O & M cost
    • 10-20% of the Cost of Energy of a wind farm (Sandia, 2006)
  – Increase annual energy production by reducing downtime

<table>
<thead>
<tr>
<th>No Surface Inspection</th>
<th>Human Visual Inspection</th>
<th>Computer-based Inspection</th>
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<tbody>
<tr>
<td>A blade incident = 26% additional cost</td>
<td>Increase total cost by 0.64% Accuracy? Uncertainty</td>
<td>Reduce labor cost 30 hours/turbine. Increase safety factor</td>
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*SGS Group: 1,000 blades/year X $75,000/blade = $75,000,000; $20,000,000/incident in 2008; labor $80/hour; UT scanner $220/day. $480,000 inspection cost/year (Nacleanenergy, 2010)
Hairline thickness crack
Challenges in the skin health monitoring of wind turbine blades
- Large scale
- On tower
  - Labor safety – injured by tools or falls
- Complex 3D geometry
- Characteristics of early defects
  - Color
  - Geometry - hairline
- Environmental noise
  - Dirt, insects, …

The methodology contains five major sections.

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<tr>
<td>Understand the determining parameters.</td>
<td>Provide a overall quick scan.</td>
<td>Examine the details of a defect.</td>
<td>Type 1 Error Type 2 Error</td>
<td>Define the severity of a crack: size, direction, and etc.</td>
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**Synthetic cracks**

*ID Brownian Motion Field images*

\[ R = \sum_{i=1}^{n} w_i z_i \]

- \( z_i \) is the intensity of the pixel associated with the mask coefficient \( w_i \).

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Rotation & open image techniques

**Sobel and Canny**

\[ \nabla f = \begin{bmatrix} \frac{\partial f}{\partial x} \\ \frac{\partial f}{\partial y} \end{bmatrix} \]

- Direction of the edge: \( \sigma(x,y) = \tan^{-1}(G_x/G_y) \)

- Optimizing threshold

**Minimize errors:**

1. Optimizing threshold #,
2. intersection of the results from two methods.
3. Opening image technique.

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**Objective**

**Motivation**

**Methodology**

**Results**

**Conclusion and Future Work**
Stage 1: Gel Coat Cracks — Generate Sample Cracks

- **Synthetic cracks**

  Characteristics may affect the detectability: (1) **Intensity level of pixels** (2) **Background noise** (3) **Uneven illumination**

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**Objective**

**Motivation**

**Methodology**

**Results**

**Conclusion and Future Work**
Representative field images

Stage 1: Gel Coat Cracks — Line detection method

- **Line detection method**
  - Able to capture hairline thickness cracks easily
  - The orientation of image is not a significant factor
  (with same threshold value)

*Same Threshold number – 0.8353*
• Linear detection method
  - Sensitive to noise
  - Does not perform well with uneven illumination

Before applying opening image technic

After applying opening image technic with line for strel function
Stage 1: Gel Coat Cracks — Edge detection method

- **Edge detection method**
  - Reduces noise significantly
    - Much smoother results
  - Effects of uneven illumination are reduced

Line detection with opening image technic

Edge detection with *Canny* method
• Challenge of optimizing threshold value for edge detection method
  – Automatically selected threshold value with Sobel or Canny method does not work well

*Sobel* with automatically selected threshold value
*Canny* with automatically selected threshold value
Stage 1: Gel Coat Cracks — Edge detection method

- Developed an algorithm to optimize threshold values

Before

![Sobel method](image1)

![Canny method](image2)

After

![Sobel method](image3)

![Canny method](image4)
Stage 1: Gel Coat Cracks — Error analysis

- Type 1 Error: false-positive identification of cracks
- Type 2 Error: failure to detect existing cracks

Type 1 Error

Type 2 Error
With threshold number equal to 0.73

Both Type 1 and Type 2 Errors
Stage 1: Gel Coat Cracks — Cracks quantification

- Quantifying a crack

Quantifying the Synthetic Crack in Group 1 - 1

Blue Rectangle: 423 - by - 301

Green approx. line function:
- \( x = 439.2590t + 202.6571 \)
- \( y = 277.2023t + 166.7593 \)
Stage 1: Gel Coat Cracks — Conclusion

• Conclusions
  – The line detection method is appropriate for quick scans
  – The edge detection method is suitable for detailed scans
  – Threshold value is critical for both methods
  – Line detection helps reduce Type 2 Error
  – Edge detection method can reduce both Types of Errors

• Future Work
  – More field image testing
  – Comparison to other methods
Stage 2: Collaborative Research @ IWES

- Task 1: Validate the method
- Task 2: Comparison to other methods
- Task 3: Field test

Pictures are from Google images.
Stage 2: Validate the method @ IWES
Stage 2: Validate the method @ IWES
Stage 2: Validate the method @ IWES

Gel coat cracks:

Severe Type 1 Error
Note: All images in the slides were resized.

Leading edge and tip Erosions:

Leading edge erosion (GE banana shape blade)

Line detection method for a quick scan
Stage 2: Understand early erosion

Goal: generate a map of a blade surface as it erodes in real time.
- Material removal history
- 3D strain map of the coating surface

Model: modified Springer’s model
- 3D complex surface with different rotational speed

Assumptions:
- Fixed velocity of a rain drop
- Constant pitch angle within one sweep
- The thickness of the coating layer varies from 0.3 to 0.6 mm
- Blade 3D model:
- Location: Homestead, IA with rain & wind data from 2008 to 2011

Prospected results
- 3D Stress map
- Material removal behavior

Part of the topic was studied by REU student Jenna Koester
Crack in the structure.

Damage in the coating.
The Comparison of Rotor Blade Health Inspection Methods

Huiyi Zhang, Ph.D. student, Iowa State University  
Major Professor: John Jackman  
Summer collaborative research at Fraunhofer IWES. Hosted by Benjamin Buchholz and Florian Sayer

Purpose: The purpose of the study is to investigate the feasibility of a computer-based wind turbine blade health inspection method in order to provide more consistent, cost-effective, and safer maintenance for wind turbine operators.

Factors to consider:

Comparative methods: In-situ testing vs. digital image processing

Number of specimens: Blade 324-6 with 27 images of defects

Inspection year: 2010, provided by WKA-Services GmbH

Specimen stability: The images were used together with the maintenance data rather than to analyze the defects. Therefore, the quality of the inspection is consistent.

Results analysis:

Characterize the defects:

- WKA identified a defect with radius, position, size, and class. However, the computer-based inspection method cannot define the radius and position without the following information: (1) entire blade image, (2) camera position.
- The computer-based inspection method quantified the defects numerically with respect to the pixels size of the defects, rather than a range offered by the site employees. It also computed the direction of the defect and the boundary box along the direction, which is usually smaller than the boundary box parallel to the coordinate system of the image.

Numerical results: See p. 3-6. The computer-based inspection method found additional hairline cracks in images 2010-14 and 2010-16. These cracks were marked with green lines on the result image.

Note:

- The size of the defects is in pixels and it can be converted to million meters once we know further information about the camera used in the project.

- The orientation of a crack, vertical or horizontal, is defined by the angle between the approximation line (also called the direction line and marked in red) and the pitch axis.

The pros and cons of the new method:

Pros:

- Consistent results with high accuracy (within a pixel).
- High speed: the time of detecting and quantifying a defect is 2-15 minutes depending on the size of the defect and the image noise.

Cons:

- False positive errors caused by the background noise (e.g., Defect 2010-23).

Criteria for acceptable performance:

Image 14 and 16 contained other hairline thickness cracks under the computer-based inspection method. Images 3, 4, 9, and 28 were sharply out of focus. Image 11, 14, 16, 23, and 25 contained false positive error generated by the background noise. However, the detected cracks were within 95% confidence zones.

Recommended minimum studies:

Next study of the current code:

- Define the class of a defect.
- Minimize false positive error.
- Identify multiple defects separately.

Image Acquisition:

- Develop automated image acquisition device.
- Provide consistency in quality of images.
- Entire blade inspection, not just the inspection of the location of the defect.

Notations:

- Boundary box parallel to the x, y axes.
- Direction line which has the minimized maximum distance to all the points along the defect edges.
- Boundary box parallel to direction line. Generally, it is smaller than the boundary box along the x, y axes.
Stage 2: Methods Comparison @ IWES

<table>
<thead>
<tr>
<th>Ser.</th>
<th>14</th>
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<tr>
<td>Radius</td>
<td>18.8</td>
</tr>
<tr>
<td>Pos.</td>
<td>VK</td>
</tr>
<tr>
<td>PT in %</td>
<td>0</td>
</tr>
<tr>
<td>Größe</td>
<td>7</td>
</tr>
<tr>
<td>Anzahl</td>
<td>1</td>
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<tr>
<td>Schaden</td>
<td>Queriss</td>
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Severe background noises

**Direction Line:**
\[ y = 0.033175 \times x + 118.6849 \]
\[ x \in [10.4681, 432.6575] \]

**Directional boundary box:**
122.4276 \times 313.0653

**Boundary box along xy axes:**
420 \times 247

Noises: dirt, insects, and so on. It is important to define the characteristics of the noises first.

Crack was not recognized.

**Note:** All the numbers are in pixels. It is necessary to know the camera info in order to convert into million meters. In addition, the location of the defect can be identified with the entire blade image.
Stage 2: Methods Comparison @ IWES

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<th>Ser.</th>
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<tbody>
<tr>
<td>17</td>
<td>22.2-23.5</td>
<td>VK</td>
<td>0</td>
<td>7-12</td>
<td>5</td>
<td>Querisse</td>
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Background noises were not detected.

Direction Line: $y = -0.09434 \times x + 143.2359 \quad x \in [263.5633, 329.112]$  
Directional boundary box: $65.8397 \times 18.5779$  
Boundary box along xy axes: $65 \times 23$

Note: All the numbers are in pixels. It is necessary to know the camera info in order to convert into million meters. In addition, the location of the defect can be identified with the entire blade image.
Direction Line:
\[ y = -0.76258 \times x + 47.32 \]
\[ x \in [-7.4104, 49.792] \]

Directional boundary box:
71.9369 \times 35.8517

Boundary box along xy axes:
47 \times 59

*Note: All the numbers are in pixels. It is necessary to know the camera info in order to convert into million meters. In addition, the location of the defect can be identified with the entire blade image. No. 28 is not focused and the defect is not clear at all.*
Stage 2: Methods Comparison @ IWES

Future work:
- Quantify defect individually from single image with multi-defects
- Distinguish defects from insects
- Setup image acquisition system
Stage 2: Image acquisition @ IWES

• Conceptual design
Stage 2: Image acquisition @ IWES

- Field test – Site 1
  - Cannot capture both side of the blade with a fixed position setup.
Stage 2: Image acquisition @ IWES

- **Field test – Site 2**
  - Visibility problem with hybrid tower and pre-bending blades.
Stage 3: Future Work

• Improve accuracy
  – Differentiate defects from insects and dirt
  – Quantify defects individually

• Develop image acquisition system

OR
• **NDI (or called NDE)**
  – The image acquisition system will consider to carry thermal camera or other device to detect structural damages

• **Aerodynamic study**
  – Aerodynamic impact due to surface roughness

• **Generator side (power output)**
  – Health blades will reduce vibration and smooth the output
  – Reduce downtime
THANK YOU
ANY QUESTIONS?