IOWA STATE UNIVERSITY

Department of Industrial and Manufacturing Systems Engineering

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

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

Major Professor

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

Minor Professor

Frank Peters
Associate Professor
Dept. of Industrial and Manufacturing Systems Engineering
Manufacturing System and Process Improvements

Committee Member

Vinay Dayal
Associate Professor,
Associate Chair for Education
Dept. of Aerospace Engineering
NDE, Composites design and inspection

Committee Member

Song Zhang
Assistant Professor
Dept. of Mechanical Engineering
Machine and computer vision, virtual reality, human-computer interaction

Committee Member

Objective

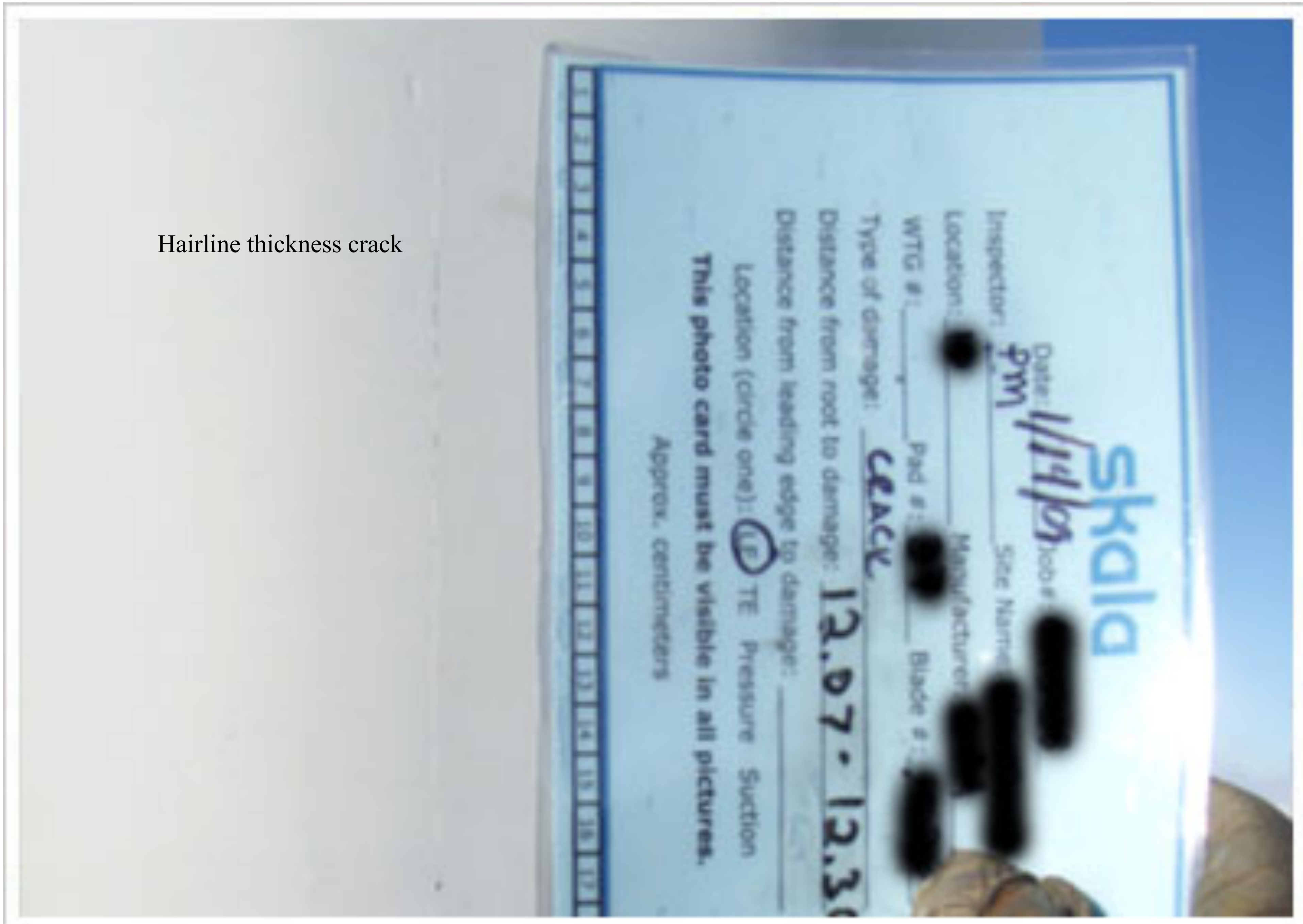
The primary objective of this research is to investigate whether wind turbine blade surface images with known cracks can be detected and if so, how much of the crack can be captured and identified with computer-based visual inspection.

Goal – automated blade inspection

Motivation

- 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

No Surface Inspection	Human Visual Inspection	Computer-based Inspection
A blade incident = 26% additional cost	Increase total cost by 0.64% Accuracy? Uncertainty	Reduce labor cost 30 hours/ turbine. Increase safety factor
*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

Surface inspection, why?

- 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, …


[1]


[2]

[1] GE Reports: http://www.gereports.com/go-go-gadget
[2] Wind blade repair: www.compositesworld.com

Stage 1: Gel Coat Cracks – Methodology

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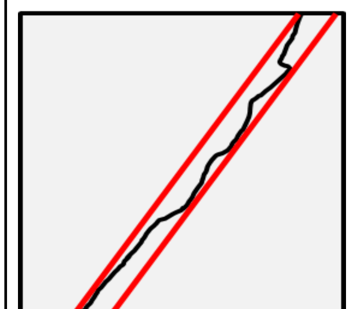
The methodology contains five major sections.

[1] **Sample crack generation**	[2] **Line detection method**	[3] **Edge detection method**	[4] **Error analysis**	[5] **Crack quantification**
Understand the determining parameters.	Provide a overall quick scan.	Examine the details of a defect.	Type 1 Error Type 2 Error	Define the severity of a crack: size, direction, and etc.
Synthetic cracks *1D 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. -1 -1 -1 / 2 2 2 / -1 -1 -1 2 -1 -1 / -1 2 -1 / -1 -1 2 -1 2 -1 / -1 2 -1 / -1 2 -1 -1 -1 2 / -1 2 -1 / 2 -1 -1 Rotation & open image techniques	*Sobel* and *Canny* $\nabla f = \begin{bmatrix} G_x \\ G_y \end{bmatrix} = \begin{bmatrix} \partial f / \partial x \\ \partial f / \partial y \end{bmatrix}$ Direction of the edge: $\alpha(x,y) = \tan^{-1}(G_x / G_y)$ Optimizing threshold T: threshold value 0: background 1: object	Minimize errors: 1. Optimizing threshold #, 2. intersection of the results from two methods. 3. Opening image technique.	

Stage 1: Gel Coat Cracks – Generate Sample Cracks

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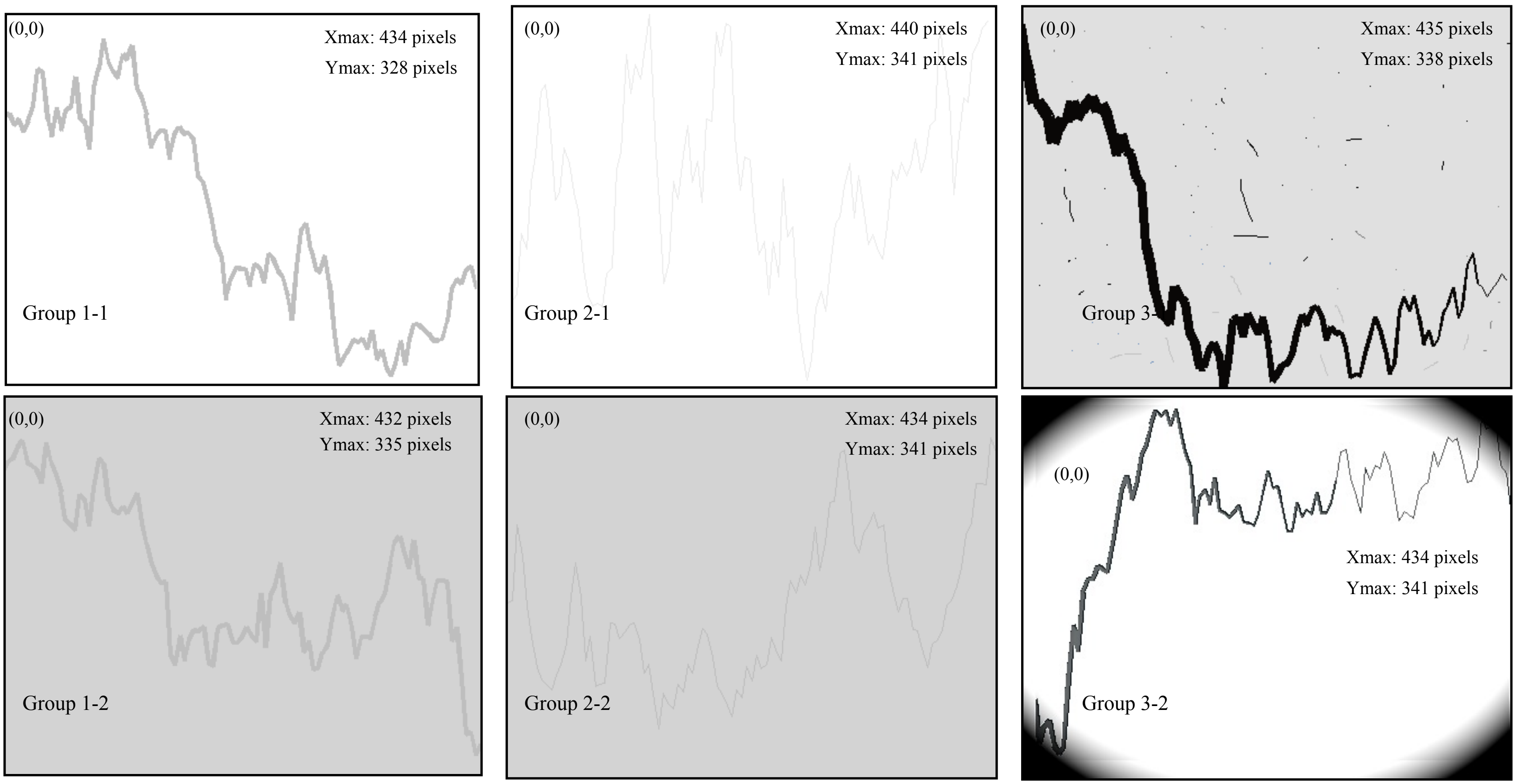
- Synthetic cracks

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



Stage 1: Gel Coat Cracks – Generate Sample Cracks

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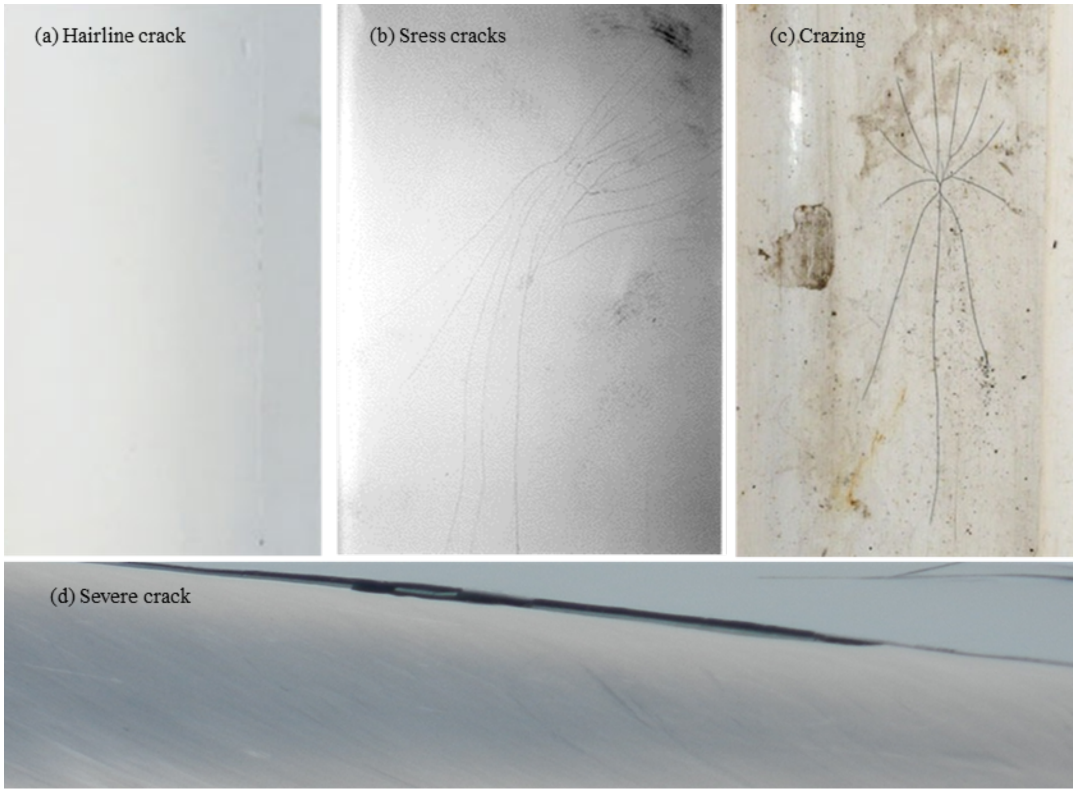
- Representative field images



Typical rotor blades surface environment – dirt and insects

(a) Hairline crack (RGB image: 157-by-272). (b) Stress cracks (Gray-scale: 247-by-350). (c) Crazing (RGB image: 270-by-435). (d) Severe crack (Gray-scale: 573-by-2673).

Stage 1: Gel Coat Cracks – Line detection method

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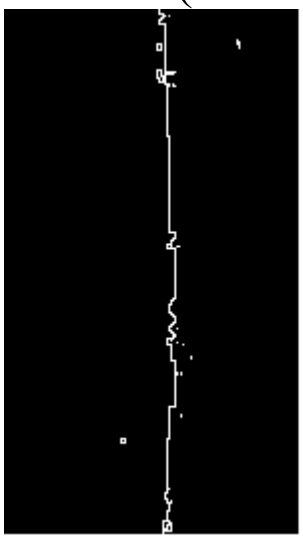
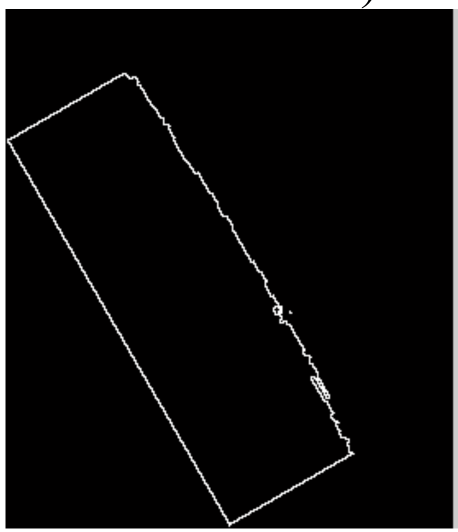
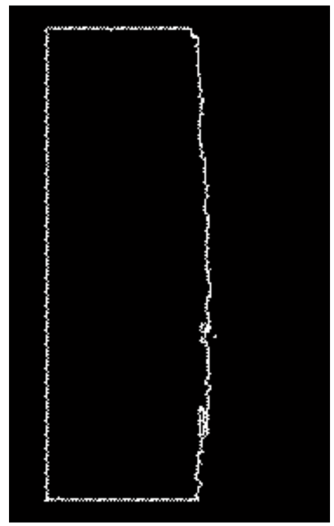
- Line detection method
  - Able to capture hairline thickness cracks easily
  - The orientation of image is not a significant factor (with same threshold value)



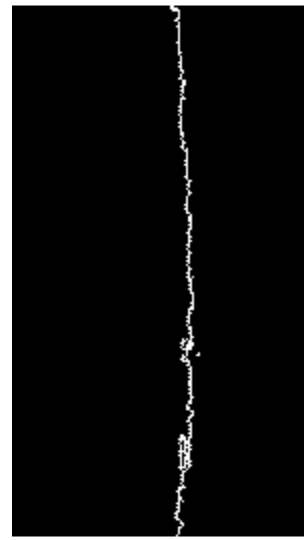
Original



Rotate 30 degree CCW
Applied the same threshold and detector masks



Rotate 30 CW

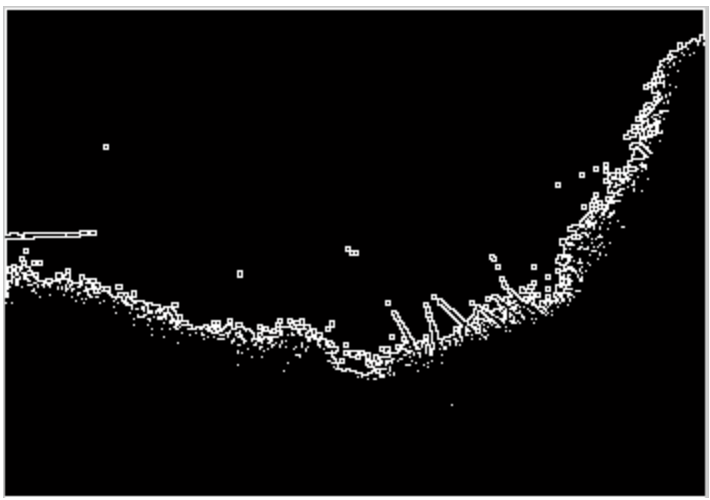


Trimmed off to the same size

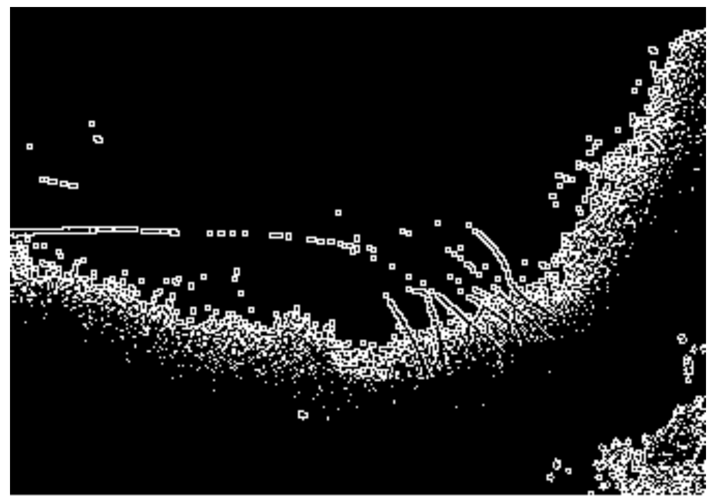
***Same Threshold number – 0.8353**

Stage 1: Gel Coat Cracks – Line detection method

- Linear detection method
  - Sensitive to noise
  - Does not perform well with uneven illumination



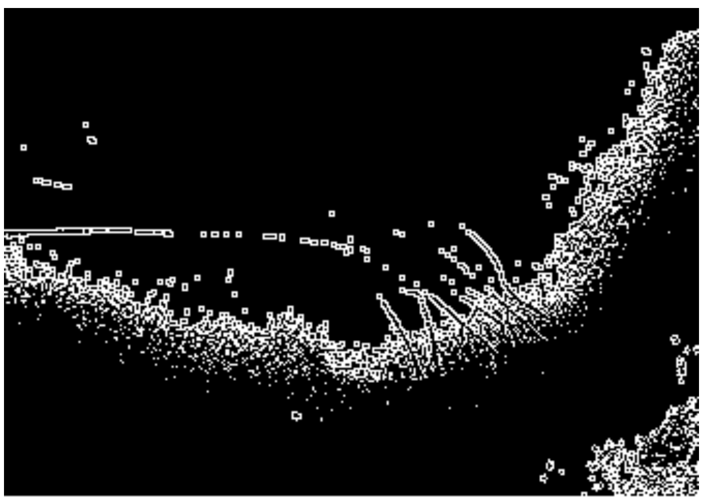
Before applying opening image technic



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

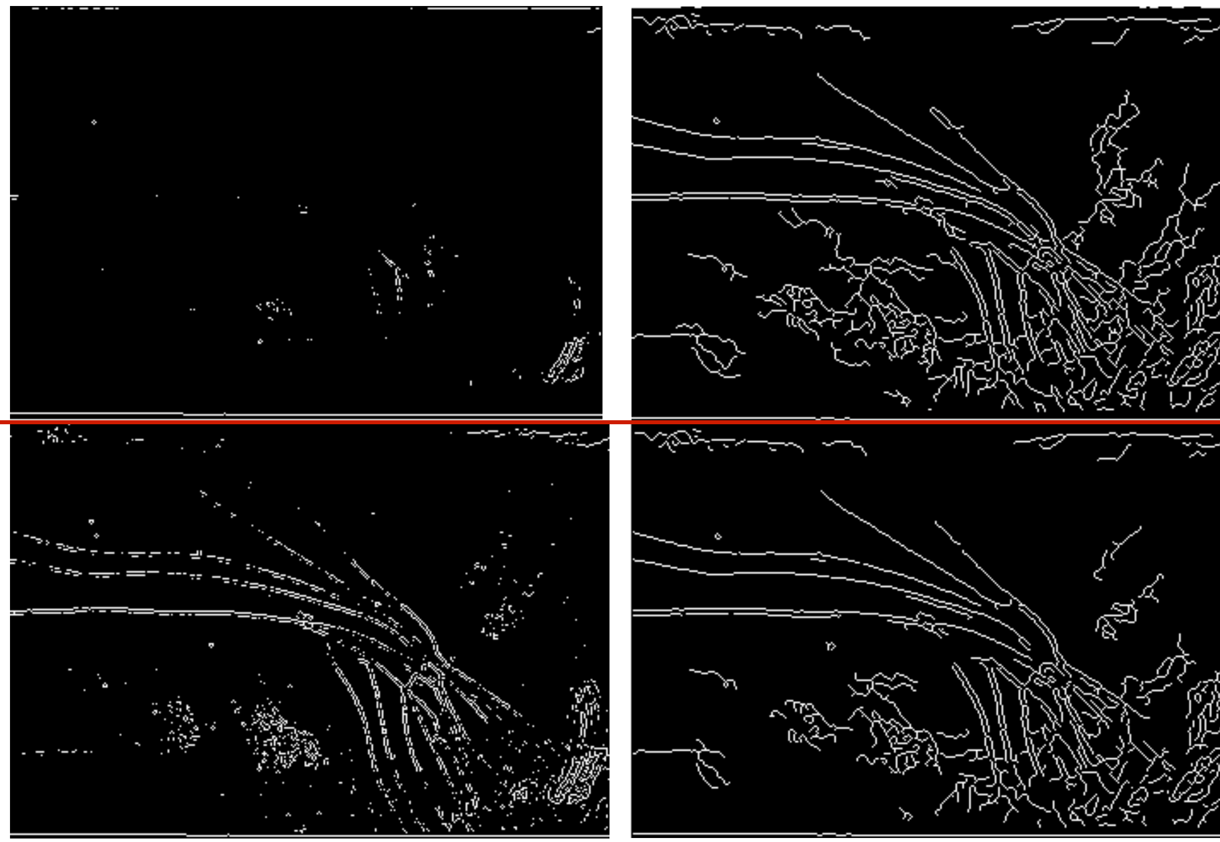
Canny with automatically selected threshold value

Stage 1: Gel Coat Cracks – Edge detection method

- Developed an algorithm to optimize threshold values

Before

After



Sobel method

Canny method

Stage 1: Gel Coat Cracks – Error analysis

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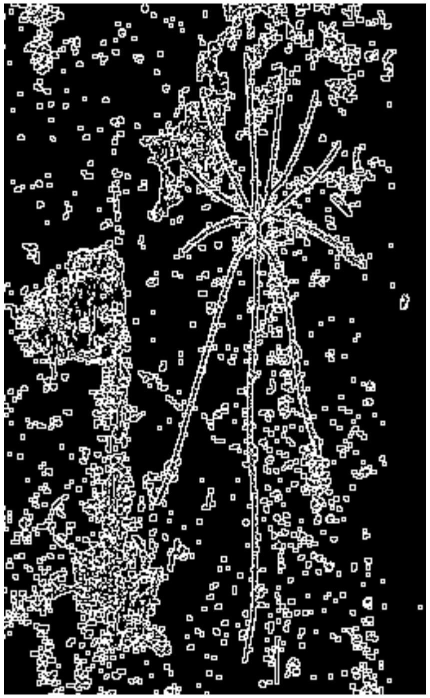
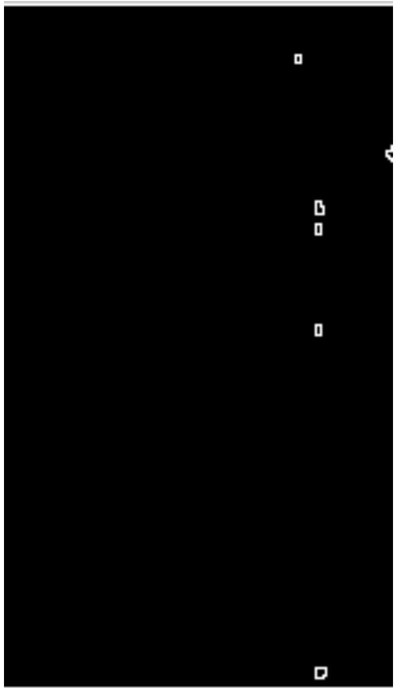
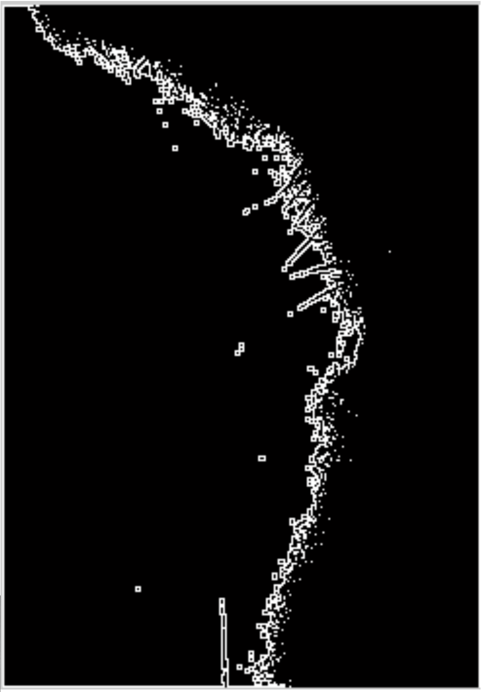
- Type 1 Error : false-positive identification of cracks
- Type 2 Error : failure to detect existing cracks

Type 1 Error

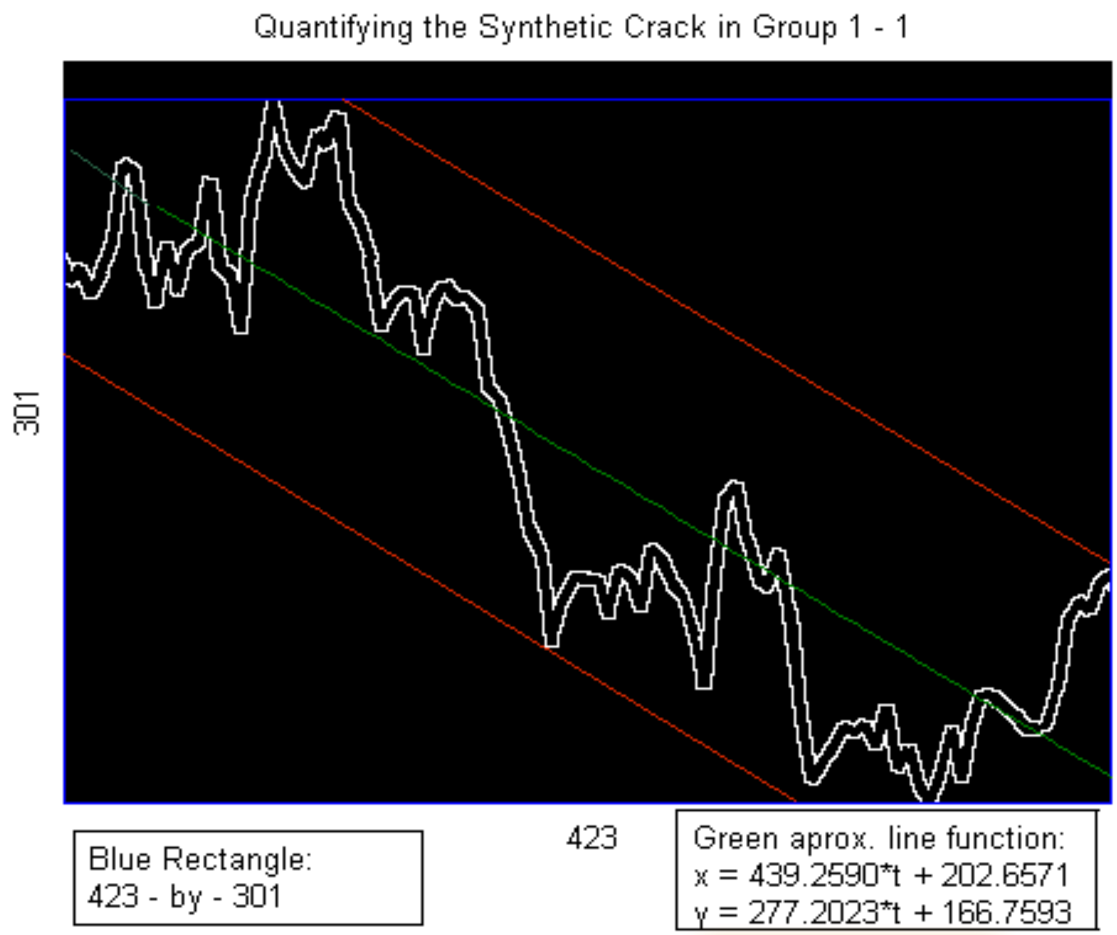



Type 2 Error
With threshold number equal to 0.73

Both Type 1 and Type 2 Errors

- Quantifying a crack



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

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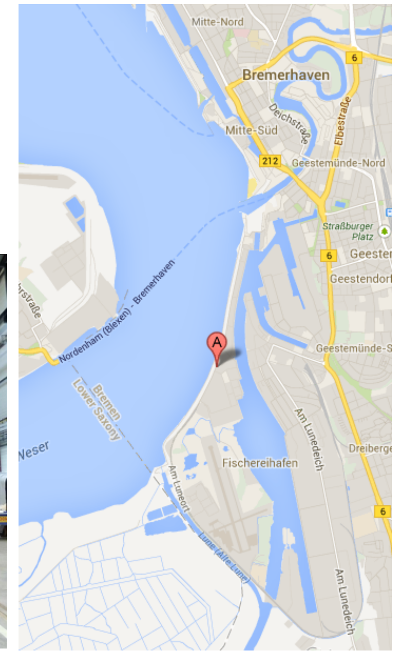
- Task 1: Validate the method
- Task 2: Comparison to other methods
- Task 3: Field test

Pictures are from Google images.



Stage 2: Validate the method @ IWES

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Stage 2: Validate the method @ IWES

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Stage 2: Validate the method @ IWES

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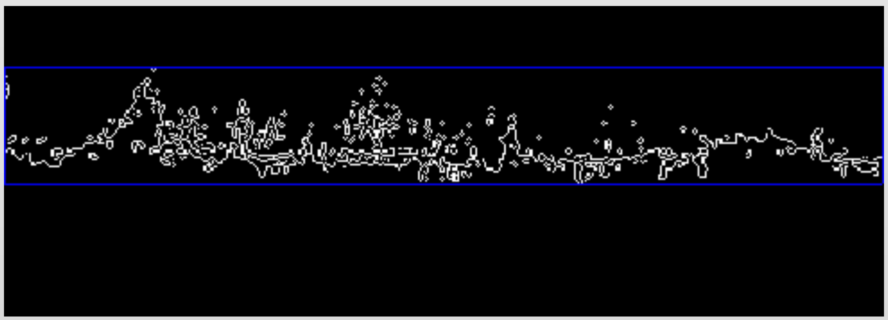
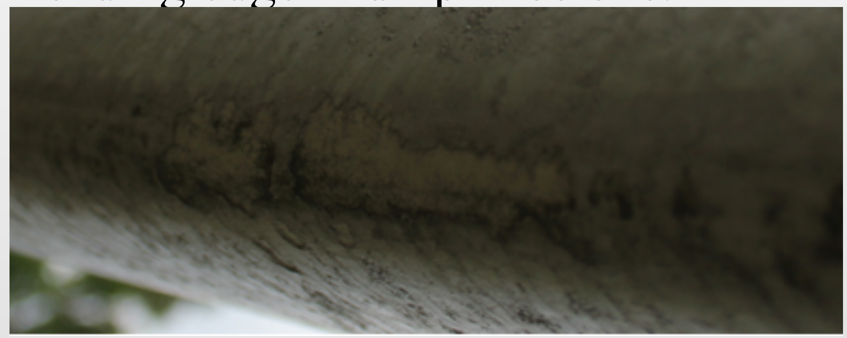
Gel coat cracks:



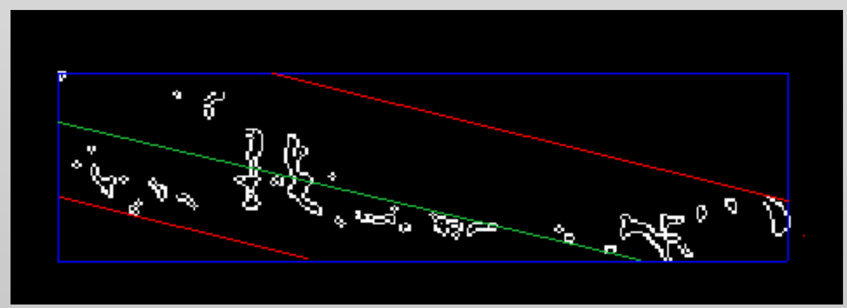
Severe Type 1 Error
Note: All images in the slides were resized.

Leading edge and tip Erosions:



Leading edge erosion (GE banana shape blade)

Line detection method for a quick scan



Stage 2: Understand early erosion

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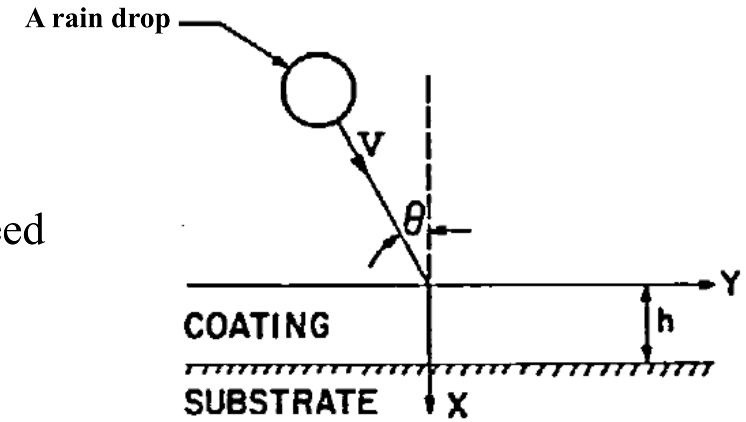
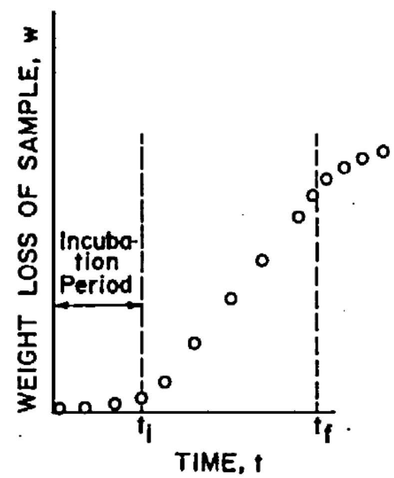
- Goal: generate a map of a blade surface as it erodes in real time.
  - Material removal history
  - 3D strain map of the coating surface
- Model: modified Springer's model
  - 3D complex surface with different rotational speed
- Assumptions:
  - Fixed velocity of a rain drop
  - Constant pitch angle 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

Stage 2: Methods Comparison @ IWES

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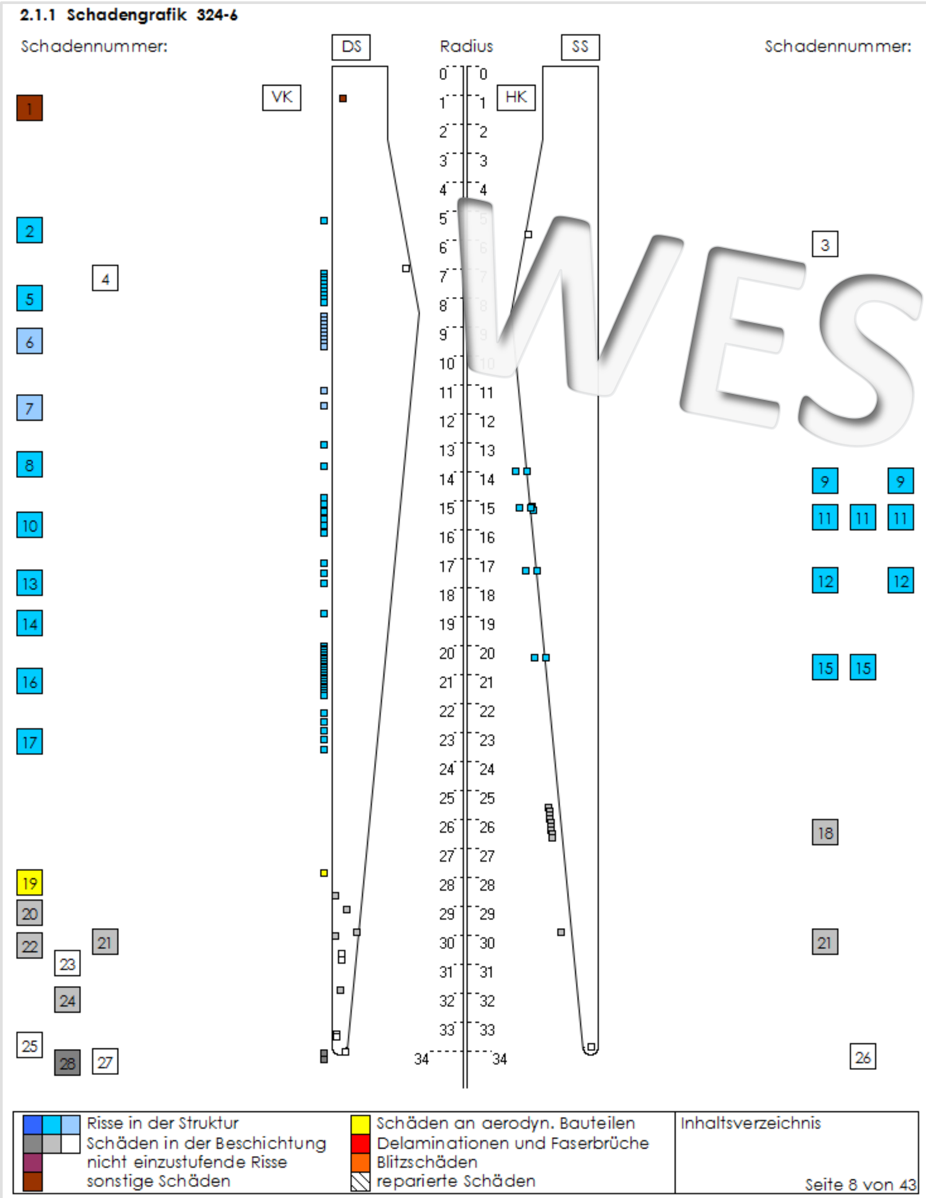

Windpark Littdorf GmbH & Co. KG c/o GLS-Beteiligungs AG Christstraße 9 44789 Bochum	**Reparaturbericht** **Nr.: 6432** Littdorf Anlagen Nr.: 15400153	**WKA-Service-Fehmarn GmbH** Gammendorf 16 D-23769 Fehmarn

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: Inspection with human eyes vs. digital image processing

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

Inspection year: 2010, provided by WKA-Service-Fehmarn GmbH

Specimen stability: The images were used to record the maintenance, rather than to analyze the defects. Therefore, the quality of the images is not 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.
- Quantify multiple defects separately.

Image Acquisition:

- Design semi-automated image acquisition device.
- Provide consistent, high quality surface images.
- Entire blade image for computing the location of the defect.

Notations:

- (green dash-dot line) Boundary box: parallel to the x, y axes.
- (red line) Direction line which has the minimized maximum distance to all the points along the defect edges.
- (blue line) Boundary box: parallel to direction line. Generally, it is smaller than the boundary box along the x, y axes.

Stage 2: Methods Comparison @ IWES

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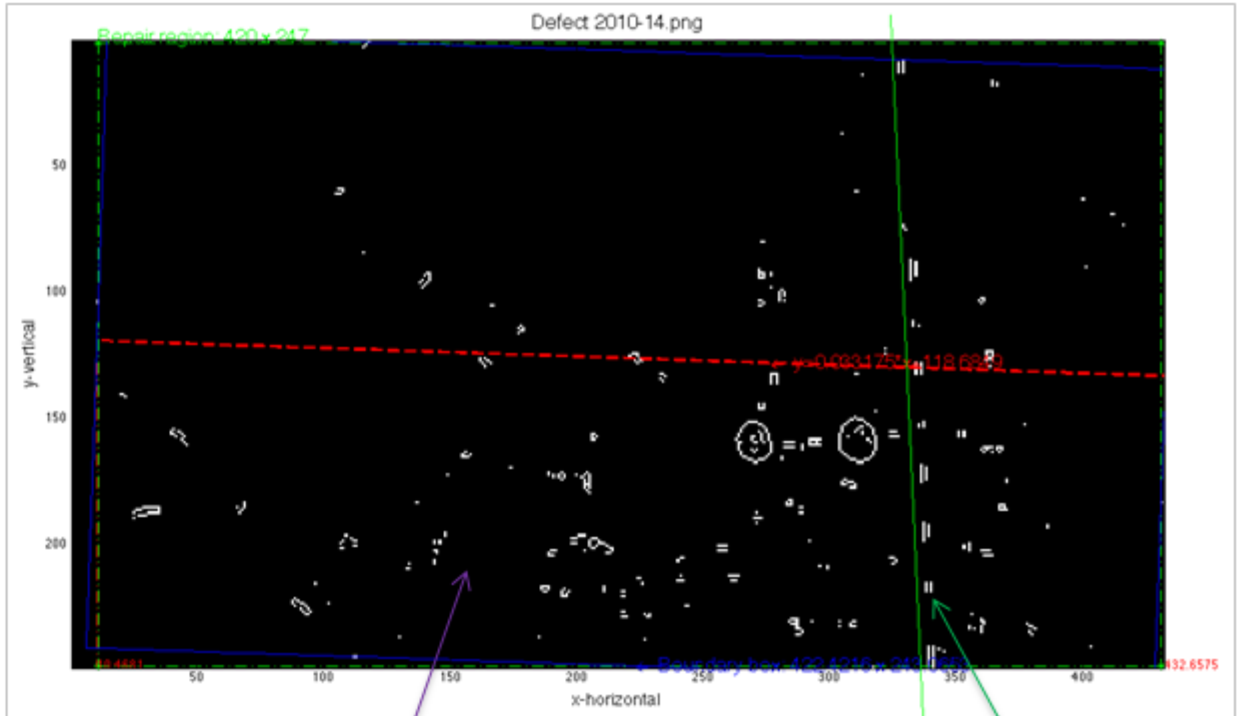
Ser.	14
Radius	18.8
Pos.	VK
PT in %	0
Größe	7
Anzahl	1
Schaden	Querriss

Severe background noises



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

Directional boundary box:
122.4276×313.0653

Boundary box along xy axes:
420×247

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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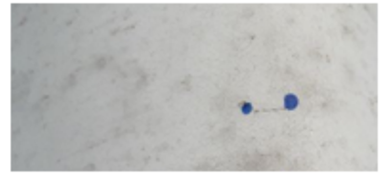
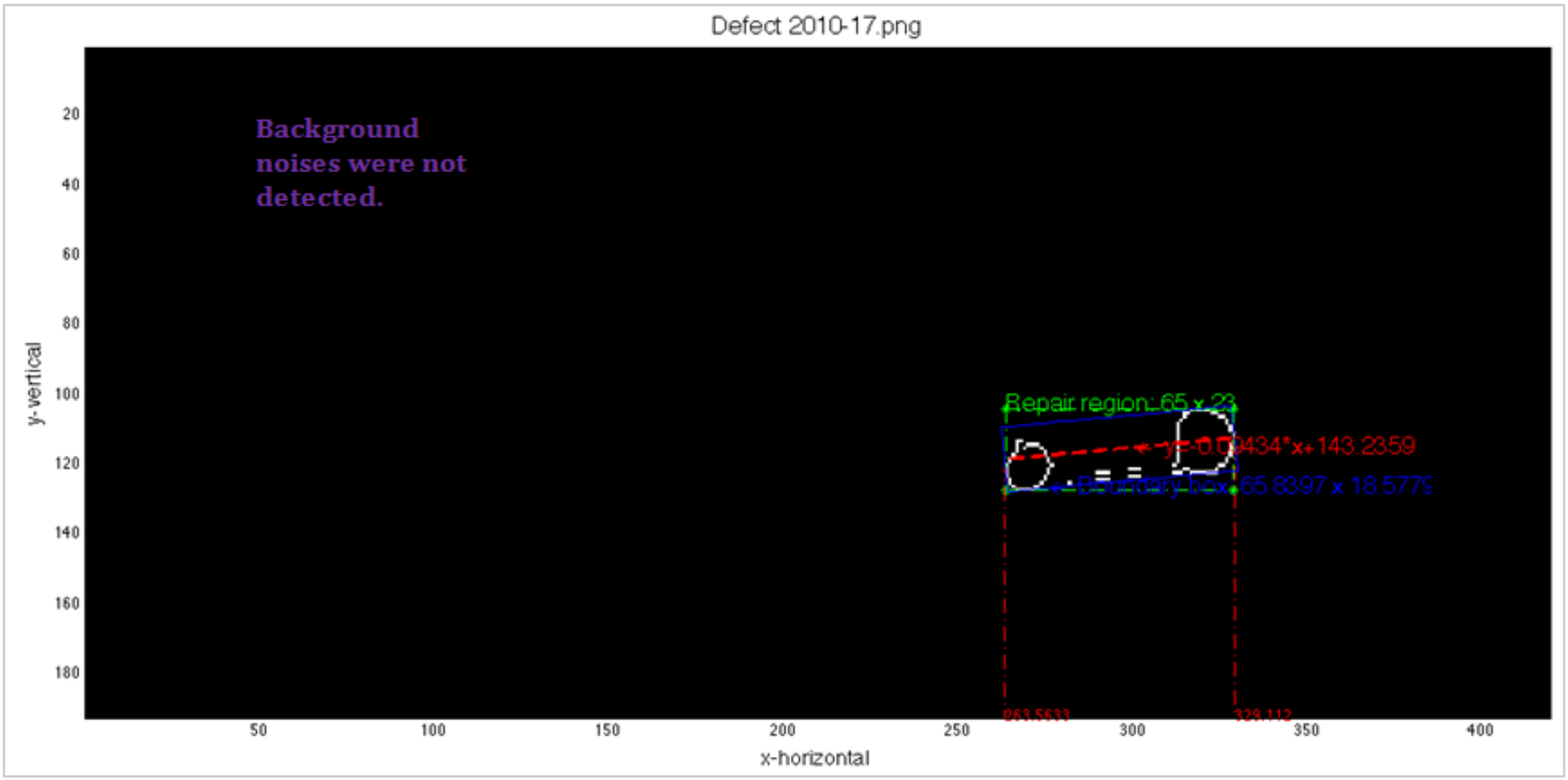
Ser.	Radius	Pos.	PT in %	Größe	Anzahl	Schaden
17	22.2-23.5	VK	0	7-12	5	Querrisse





Direction Line: $y = -0.09434 * x + 143.2359 \quad x \in [263.5633, 329.112]$

Directional boundary box: 65.8397×18.5779 **Boundary box along xy axes:** 65×23

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.

Stage 2: Methods Comparison @ IWES

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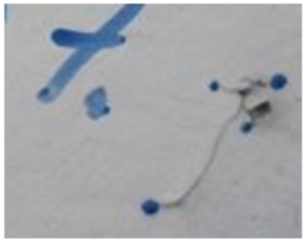
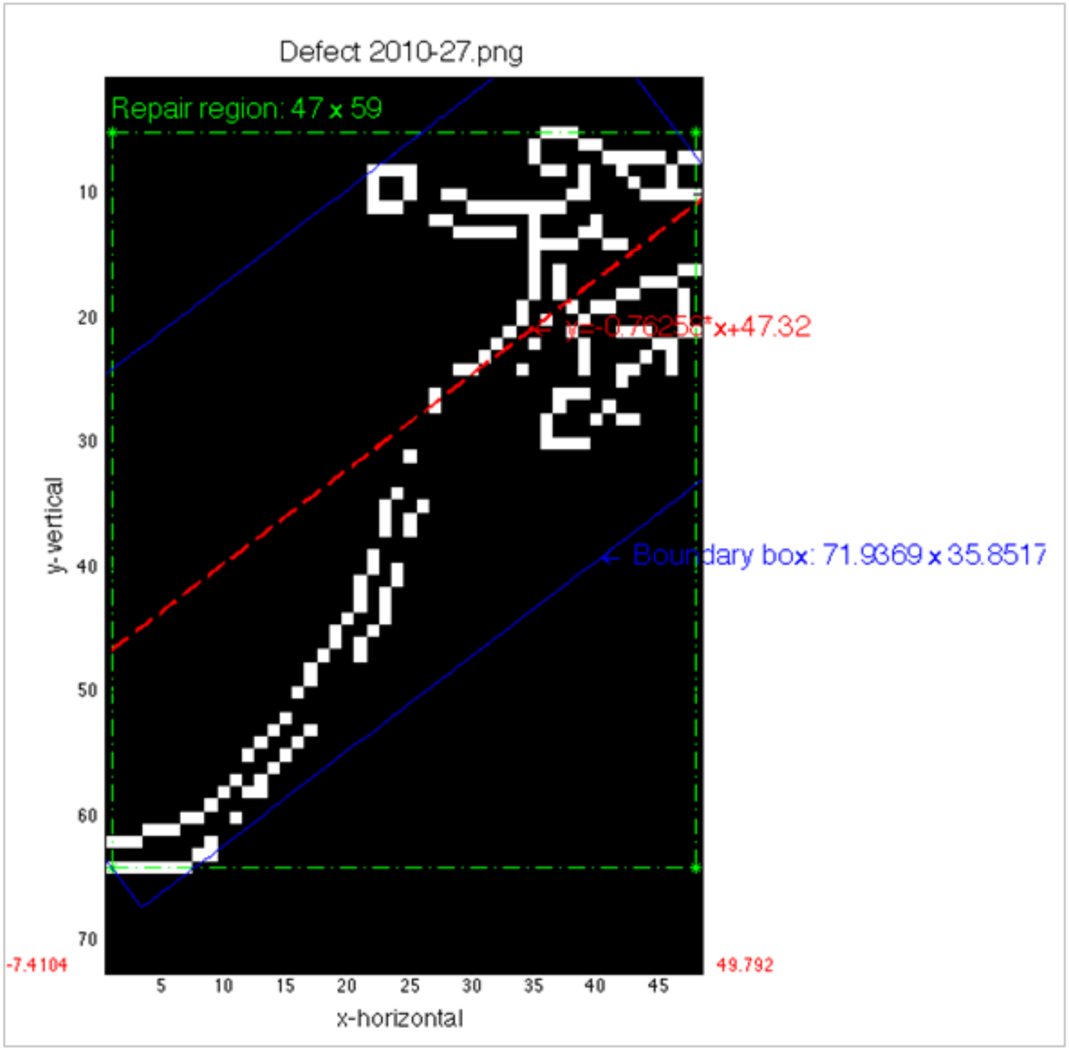
Ser.	27
Radius	33.9
Pos.	DS
PT in %	95
Größe	22
Anzahl	1
Schaden	Verzeigter Riss



Direction Line:
$y = -0.76258 * x + 47.32$
$x \in [-7.4104, 49.792]$

Directional boundary box:
71.9369×35.8517

Boundary box along xy axes:
47×59



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

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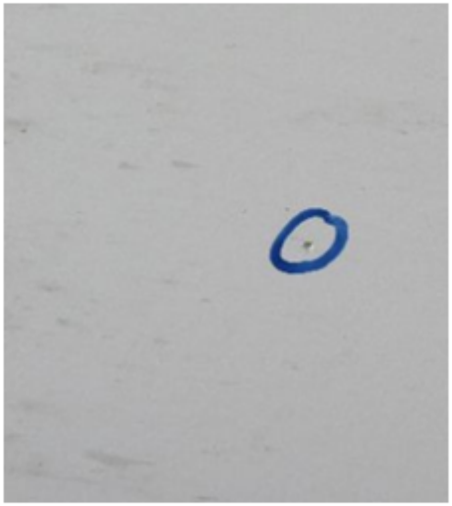
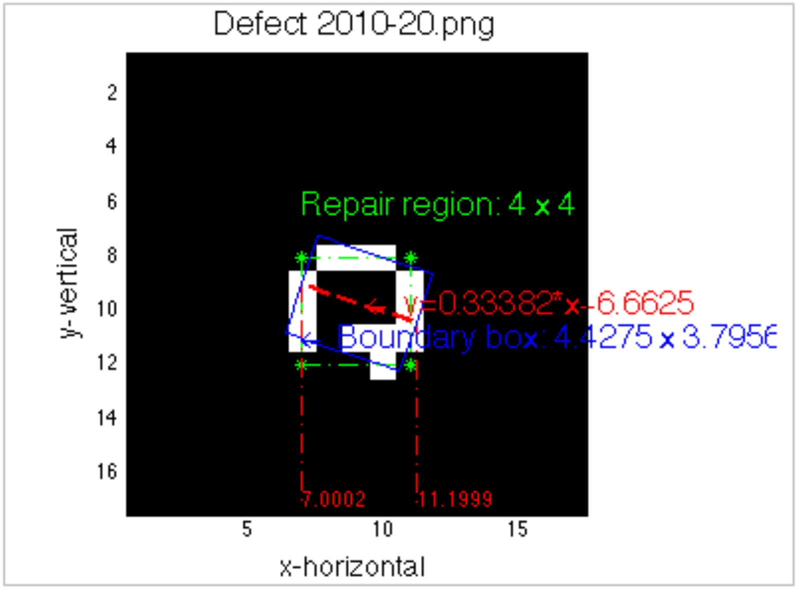
Ser.	20
Radius	28.5-29
Pos.	DS
PT in %	10-40
Größe	3-4
Anzahl	2
Schaden	Abplatzungen in der Beschichtung





Direction Line:
$y = 0.33382 * x + 6.6625$
$x \in [7.0002, 11.1999]$
Directional boundary box: 4.4275×3.7956
Boundary box along xy axes: 4×4

- Future work:
  - Quantify defect individually from single image with multi-defects
  - Distinguish defects from insects
  - Setup image acquisition system

Stage 2: Image acquisition @ IWES

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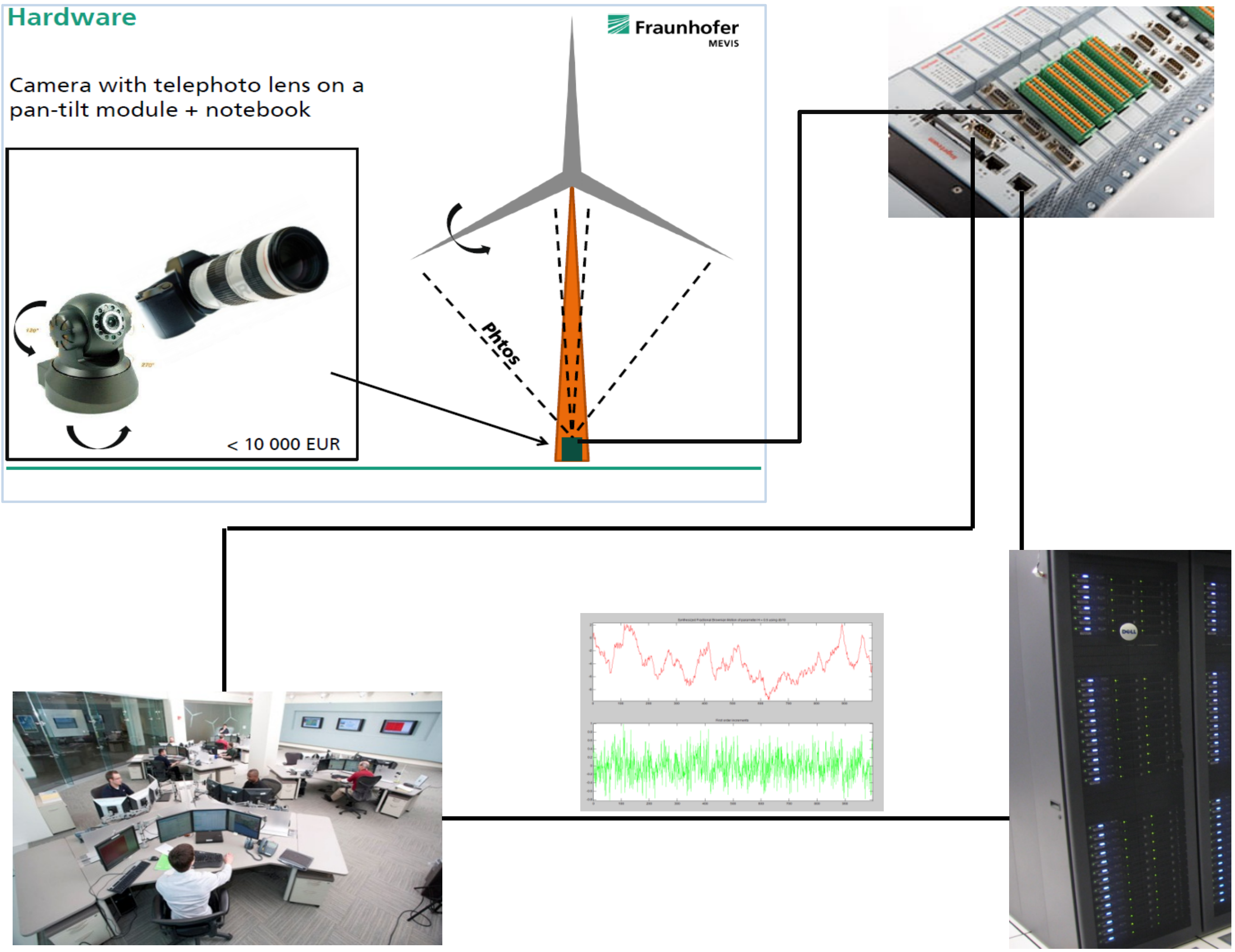
- Conceptual design



Stage 2: Image acquisition @ IWES

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- Field test – Site 1
  - Cannot capture both side of the blade with a fixed position setup.

Stage 2: Image acquisition @ IWES

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- Field test – Site 2
  - Visibility problem with hybrid tower and pre-bending blades.

Stage 3: Future Work

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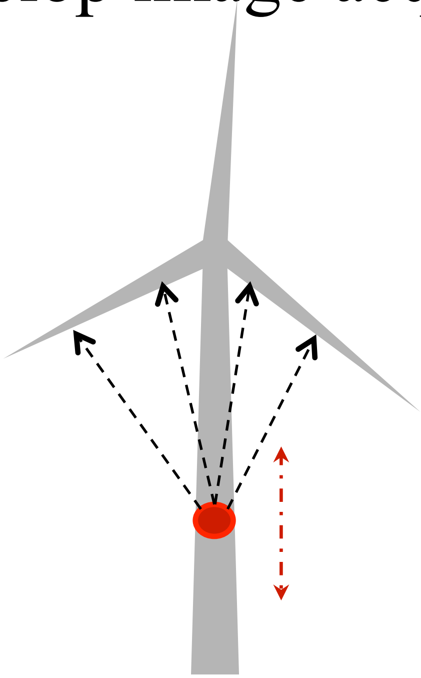
- Improve accuracy
  - Differentiate defects from insects and dirt
  - Quantify defects individually
- Develop image acquisition system



OR

Relationship to the work of other WESEP students

- 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?