Defect Detection in Electroluminescence (EL) Images of Solar Cells

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CSE 4128: Image Processing and Computer Vision Laboratory

1. Problem Statement & Motivation

Electroluminescence (EL) imaging is widely used in photovoltaic manufacturing and maintenance to reveal otherwise invisible defects (micro-cracks, shunts, broken fingers/busbars, hotspots). However, EL images also contain strong grid lines (cell borders, busbars) and uneven illumination that can confuse standard edge/threshold methods.

Goal: Build a classical image-processing pipeline that *(i)* suppresses the grid, *(ii)* enhances crack-like patterns, and *(iii)* outputs a clean binary defect mask and a thinned crack skeleton, enabling measurements such as crack length and busbar integrity.

2. Proposed Method (Overview)

Our pipeline combines spatial and frequency-domain processing with morphological post-processing and line modeling. The stages are:

1. **Preprocessing (Denoise & Contrast)**: Histogram equalization + Gaussian smoothing (σ tuned) reduce sensor noise while preserving crack ridges.
2. **Grid/Illumination Suppression**:
   - *Adaptive Gaussian Thresholding* to reveal cell boundaries and busbars.
   - *FFT notch filtering* to remove periodic row/column components caused by the panel grid.
3. **Crack & Line Candidate Extraction**:
   - *Canny edge detection* to get high-confidence, thin edges.
   - *Hough transform* to estimate dominant grid directions and exclude them ($\pm\theta$).
   - *Crack score map*: blend of high-pass response (from FFT) and edge magnitude.
4. **Binary Segmentation & Cleaning**:
   - *Thresholding* (Otsu or Sauvola) on the crack score map.
   - *Morphology* (open/close, small-component removal) to reduce noise and stitch short gaps.
5. **Skeletonization & Measurements**:
   - *Medial-axis/skeleton* of the defect mask for crack length estimation (px or mm with calibration).
   - *Region descriptors*: area, perimeter, eccentricity, orientation, bounding box.
   - *Busbar integrity*: continuity score along detected busbar lines.

3. Mathematical Image Processing Components

Convolution (Denoising): Gaussian kernel

$$G_\sigma(x, y) = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{x^2 + y^2}{2\sigma^2}\right), \quad I_G = I * G_\sigma.$$

Segmentation (Adaptive Gaussian Thresholding):

$$T(x,y) = \mu_{\mathcal{N}}(x,y) - C, \qquad B(x,y) = \begin{cases} 1, & I_G(x,y) < T(x,y) \\ 0, & \text{otherwise,} \end{cases}$$

with local Gaussian-weighted mean $\mu_{\mathcal{N}}$.

Edge Detection (Canny): gradient magnitude $M = \sqrt{I_x^2 + I_y^2}$, non-max suppression, and hysteresis thresholds $[t_L, t_H]$.

Thresholding (Otsu/Sauvola):

$$T_{\text{Sauvola}} = \mu \left[1 + k\left(\frac{\sigma}{R} - 1\right)\right], \quad \text{or} \quad T_{\text{Otsu}} = \arg\max_T \text{ between-class variance.}$$

Morphology: opening/closing with structuring element S to remove speckles and close gaps.

Frequency Domain: FFT $F(u,v)$ with circular or directional *notch* filters $H(u,v)$ to attenuate periodic grid frequencies: $\hat{F} = F \cdot H$.

Hough Line Transform: voting in (ρ, θ) to detect lines; lines near grid orientations are excluded by an angle deviation bound $\pm\Delta\theta$.

Region Descriptors: area, perimeter, eccentricity, major/minor axes from second moments; crack length is the total skeleton pixel count (or $\times$ pixel size for mm).

4. Experimental Setup (Key Parameters)

Below are typical settings that produced the attached results. Parameters can be tuned per dataset.

Stage	**Value(s)**
Gaussian blur	kernel 5×5, $\sigma = 1.0$
Adaptive threshold	block 31, $C = 6$ (Gaussian)
Canny	low = 25, high = 90
Hough	threshold = 150, min length = 130, gap = 8
Grid angles exclusion	$\Delta\theta = 12°$ around $\{0°, 90°\}$
Morphology	open 3, close 3; min region area ≥ 120 px
FFT notch	radius = 6, offsets: $(0,35), (0,-35), (35,0), (-35,0)$

5. Visual Results (Input & Expected Output)

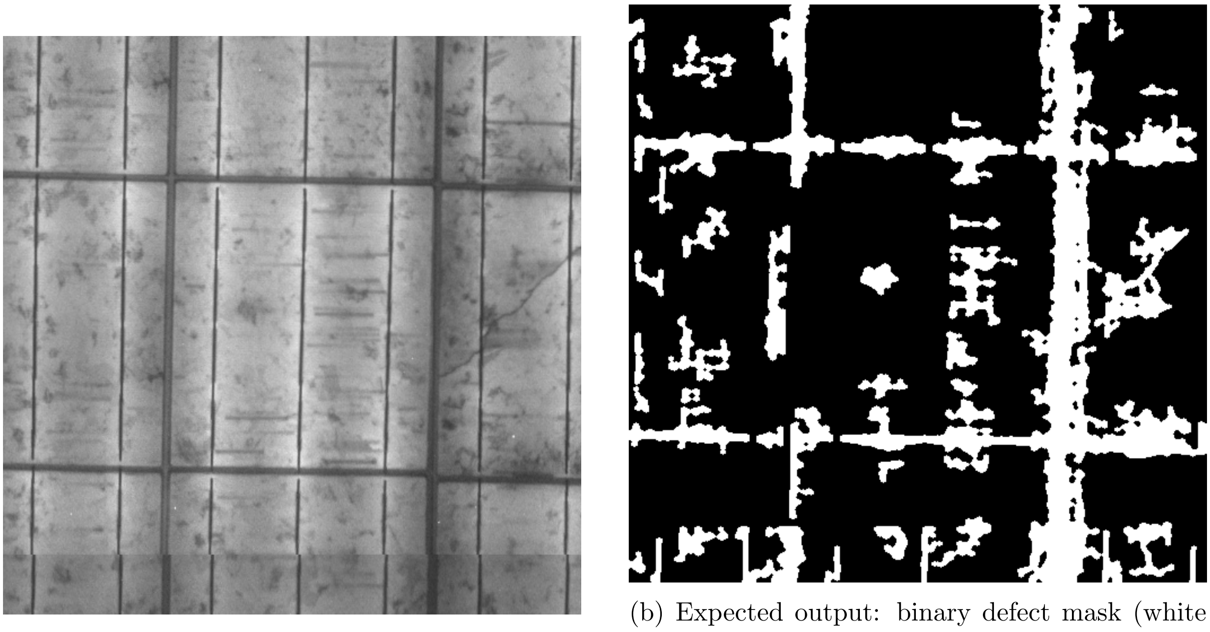
Figures below are the exact visuals required by the assignment.
Optional (for supplementary page): overlay and crack skeleton.

6. Expected Measurements (if reported)

If available, we will report: (i) number of defect regions, (ii) total crack length (skeleton pixels), (iii) count of Hough lines removed (grid), and (iv) busbar integrity score (fraction of continuous pixels along each busbar).

7. Why This Will Work

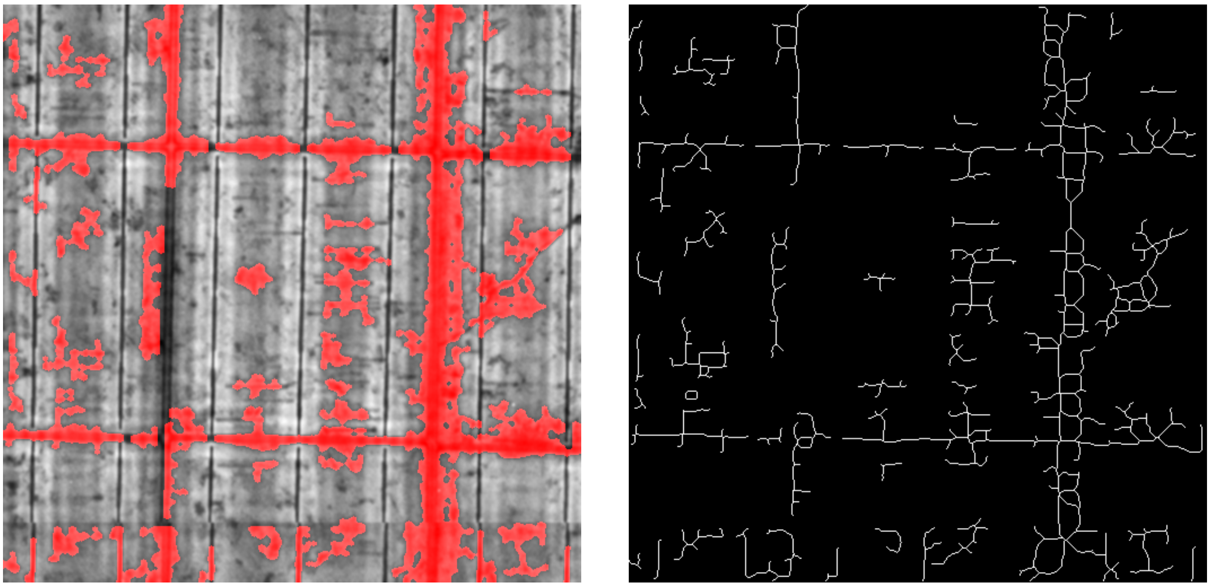
The method targets the failure modes of naive processing in EL: (i) strong grid lines are explicitly modeled and removed (Hough + notch); (ii) subtle, curvilinear cracks are enhanced (high-pass



(a) Input EL image

(b) Expected output: binary defect mask (white = defects)

Figure 1: Input and expected output of the proposed pipeline.



(a) Defect mask overlaid on EL image

(b) Thinned crack skeleton

Figure 2: Qualitative verification (optional figure).

+ Canny); (iii) adaptive thresholding handles illumination variation; and (iv) morphology & skeletonization deliver clean, measurable structures. Together these achieve **sub-millimeter** localization when pixel-to-mm is known.

8. Limitations & Next Steps

Limitations: sensitive to parameter choices across very different panels; thick soiling or severe banding can mimic cracks. **Next:** robust auto-tuning (noise/adaptive thresholds), multi-scale line suppression, and optional CNN post-filter to reject texture false positives.