YOLO Ensemble for UAV-based Multispectral Defect Detection in Wind Turbine Components

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Deep Learning

YOLOv8 + specialized thermal model

UAV Inspection

Multispectral data collection

Wind Turbines

Defect detection in blades, towers, motors

Performance

mAP@.5: 0.93 | F1-score: 0.90

Abstract

Research Overview

0.93 mAP@.5

0.90 F1-Score

Enhanced defect detection in wind turbine components through **YOLO ensemble** integrating visible and thermal channels from UAV inspections. Combines general-purpose YOLOv8 with specialized thermal model using **bounding box fusion algorithm**, outperforming standalone models.

UAV Inspection

Advanced sensors enable monitoring of wind turbine blades, towers, and critical components

Multispectral Fusion

Integration of RGB and thermal imagery for enhanced defect visibility

YOLO Ensemble

Sophisticated fusion algorithm improves detection of both visual and thermal defects

Introduction

Inspection Challenges

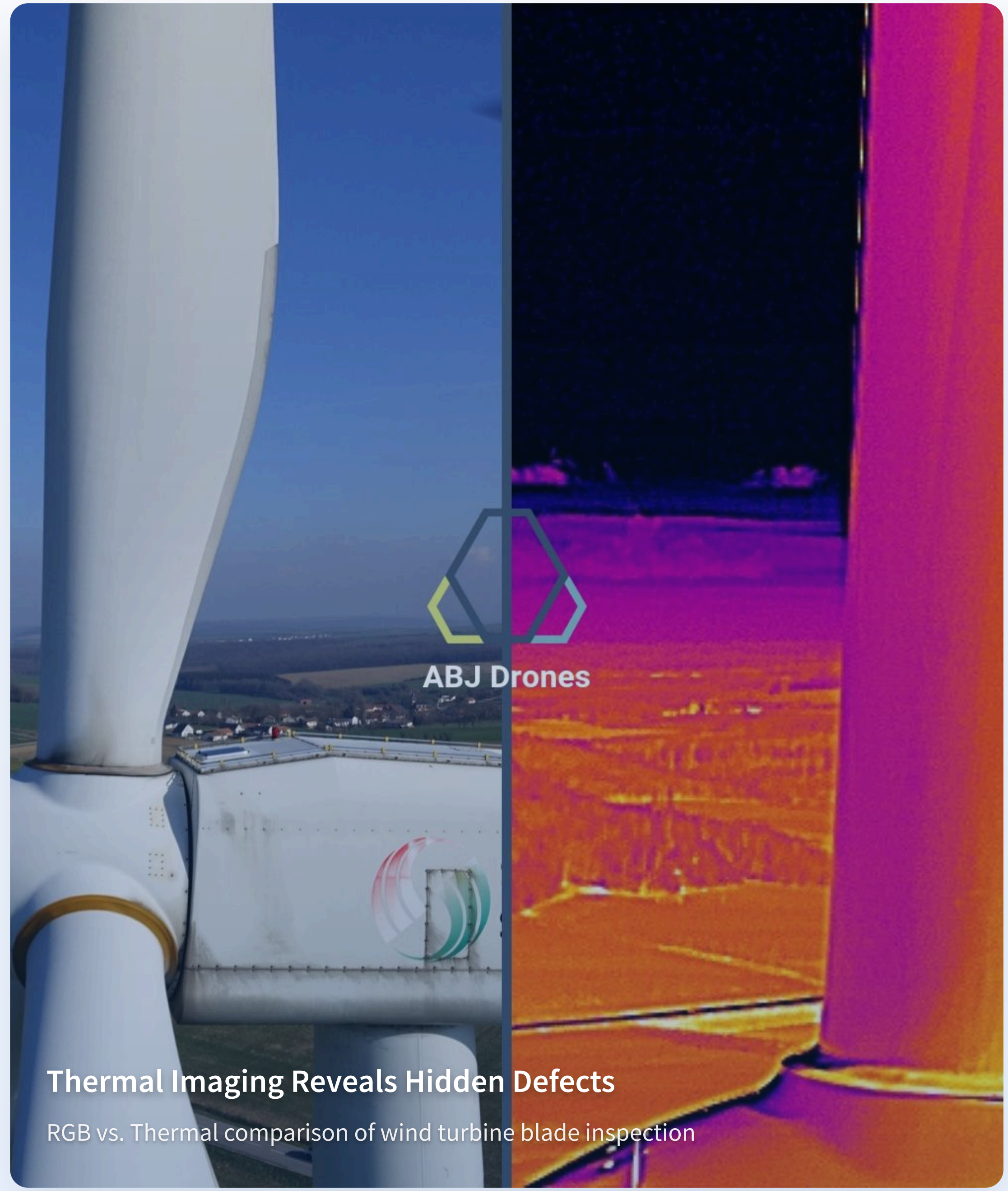
- Minor defects → **economic & safety risks**
- Timely maintenance → **efficiency & longevity**
- Complex geometries & remote locations

UAV-Based Inspection

- **High-resolution optical sensors** & thermal cameras
- Efficient data collection from multiple angles
- Captures defects invisible in RGB images

Data Processing

- Large data volumes → **real-time processing**
- Environmental conditions affect quality
- Robust algorithms for multispectral data



Thermal Imaging Reveals Hidden Defects

RGB vs. Thermal comparison of wind turbine blade inspection

Related Work

Sensing Evolution

- **RGB sensors** with basic ML
- **Thermal cameras** for temperature anomalies
- **Multispectral sensors** for early corrosion
- **5G networks** & edge computing

Algorithm Evolution

- **Hand-crafted features** classifiers
- **Deep learning** for defect patterns
- **YOLO** for real-time detection
- **Faster/Cascade R-CNN** for precision

Fusion Evolution

- **Simple averaging** of RGB & IR data
- **CNN-based fusion** learning strategies
- **Ensemble methods** combining detectors
- **Research gap** in multispectral ensembles

State-of-the-Art

- **Multispectral data** with advanced CNNs for reliable detection
- **Ensemble techniques** balance speed & accuracy for real-time inspection
- **RGB-IR fusion** effectively reduces missed defects

Methodology Overview

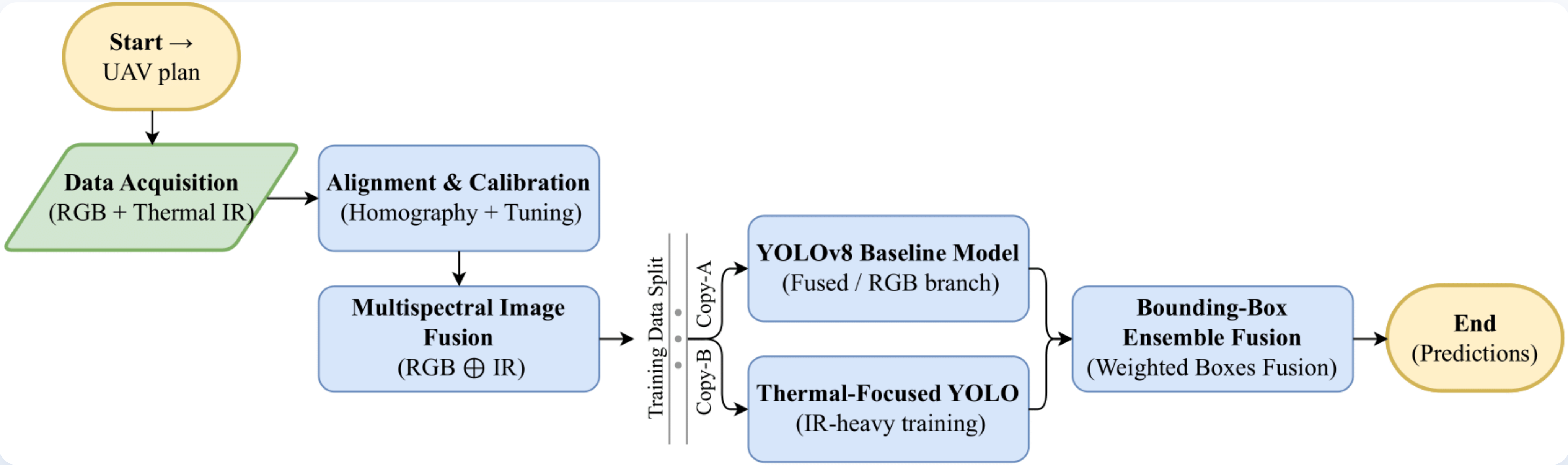


Figure 1: General workflow of our proposed ensemble approach

1

Data Acquisition

UAVs capture **RGB** and **thermal IR** imagery

2

Multispectral Fusion

Homography-based registration for precise alignment

3

Parallel Training

YOLOv8 and **specialized thermal model**

4

Ensemble Fusion

Weighted bounding-box fusion algorithm

Data Collection and Fusion

RGB Channel

- **High-resolution** optical images (4K/6K)
- Detailed textural & color information
- Essential for **surface cracks** & corrosion

IR Channel

- **Co-located infrared camera** capture
- Detects temperature-related anomalies
- Reveals **subsurface defects** invisible in RGB

Multispectral Image Fusion

1. **Precise pixel-wise alignment** of IR to RGB
2. **Homography-based registration** for focal length differences
3. Fusion function: weighted sum to deep learning models (IFCNN)
4. Creates enriched representations for diverse defect detection

Fusion Function

$$\mathrm{Fusion}(x,y) = f(\mathrm{RGB}(g_x(x,y), g_y(x,y)), \mathrm{IR}(h_x(x,y), h_y(x,y)))$$

Where g_x, g_y and h_x, h_y represent geometric transformations applied to RGB and IR images, and $f(\cdot,\cdot)$ is the fusion function

YOLO Models

YOLOv8 Baseline

- **High-speed inference** with state-of-the-art accuracy
- Ideal balance for **near real-time** UAV inspection
- Trained on both RGB and fused multispectral images

Thermal Model (Mt)

- Exclusively trained on **IR-heavy data**
- Heightened sensitivity to subtle thermal gradients
- Detects defects often overlooked by general-purpose models

Defect Classes

Cracks

C1

Structural fractures compromising aerodynamic integrity

Detection: Visible surface fractures in blades, towers

Corrosion

C2

Oxidative degradation on metallic surfaces

Detection: Primarily on tower and blade root connections

Overheating

C3

Temperature anomalies indicating mechanical/electrical faults

Detection: Primarily via IR channel in nacelle components

Ensemble Fusion Algorithm

Bounding Box Fusion

1. Identify **overlapping boxes** of same class from both models
2. Calculate **weighted averages** of confidence & parameters
3. Create fused detection with combined information
4. Preserve unique findings from each model
5. Apply **Non-Maximum Suppression** to remove redundancies

Weighted Average Formulas

$$p_{ensemble} = \gamma p_{Mt,j} + (1-\gamma) p_{y,i}$$

$$x_{ensemble} = \gamma x_{Mt,j} + (1-\gamma) x_{y,i}$$

$$y_{ensemble} = \gamma y_{Mt,j} + (1-\gamma) y_{y,i}$$

$$W_{ensemble} = \gamma W_{Mt,j} + (1-\gamma) W_{y,i}$$

$$H_{ensemble} = \gamma H_{Mt,j} + (1-\gamma) H_{y,i}$$

Where $\gamma \in [0, 1]$ controls the contribution of each model

Weighting Factor

$\gamma = 0.5$ assigns equal importance to both models

NMS Threshold

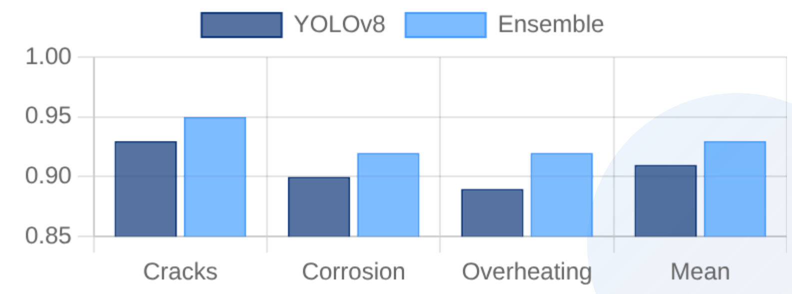
Removes boxes with IoU above threshold τ_{nms}

Results - Performance Comparison

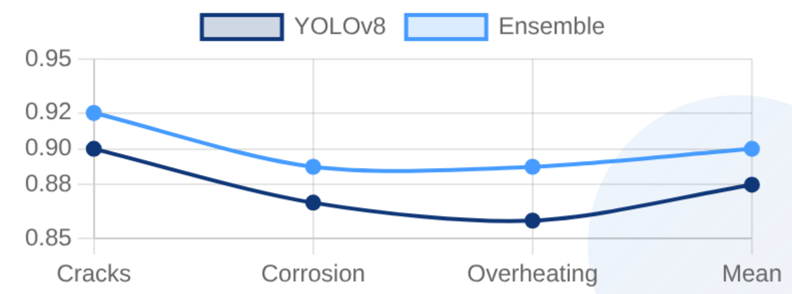
YOLOv8 vs. Ensemble Performance

Defect Class	mAP@.5		mAP@.5:.95		Precision		F1-Sc
	YOLOv8	Ensemble	YOLOv8	Ensemble	YOLOv8	Ensemble	YOLOv8
Cracks (C1)	0.93	**0.95**	0.78	**0.81**	0.91	**0.93**	0.90
Corrosion (C2)	0.90	**0.92**	0.75	**0.78**	0.88	**0.90**	0.87
Overheating (C3)	0.89	**0.92**	0.74	**0.77**	0.87	**0.90**	0.86
Mean	0.91	0.93	0.76	0.79	0.89	0.91	0.88

mAP@.5 Comparison



F1-Score Comparison



Overall Improvement

Ensemble achieves **+2.2%** mAP@.5 and **+3.9%** mAP@.5:.95 over single model

Thermal Defects

Overheating detection shows **+3.4%** improvement in mAP@.5 with specialized model

Balanced Performance

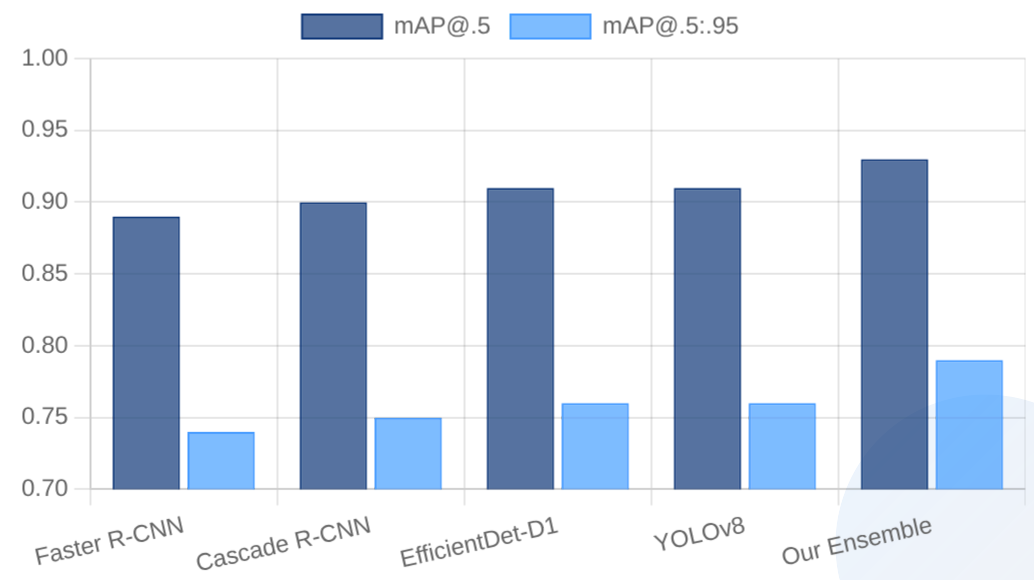
Ensemble maintains high precision while reducing false negatives across all defect types

Results - State-of-the-Art Comparison

Performance Comparison

Model	mAP@.5	mAP@.5:.95
Faster R-CNN	0.89	0.74
Cascade R-CNN	0.90	0.75
EfficientDet-D1	0.91	0.76
YOLOv8	0.91	0.76
Our Ensemble OURS	**0.93**	**0.79**

Visual Comparison



Top Performance

Our ensemble achieves **highest mAP@.5 (0.93)** and **mAP@.5:.95 (0.79)** among all models

Single-Stage Advantage

Single-stage detectors (YOLOv8, EfficientDet) outperform two-stage approaches in speed-accuracy balance

Ensemble Benefits

Fusion of YOLOv8 with specialized thermal model provides **+3.9%** improvement in stricter mAP@.5:.95 metric

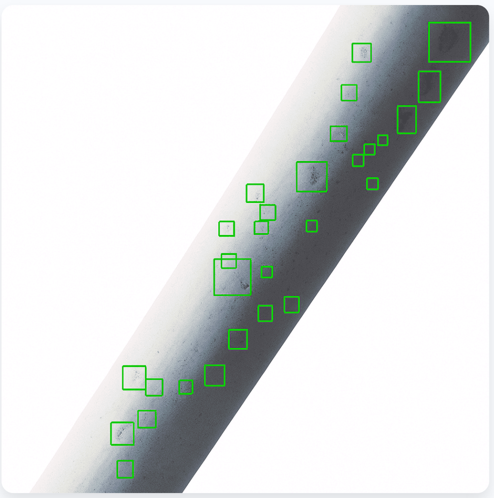
Results - Qualitative Analysis

Comparison of RGB images vs. fused multispectral images demonstrates enhanced defect visibility

Blade Cracks

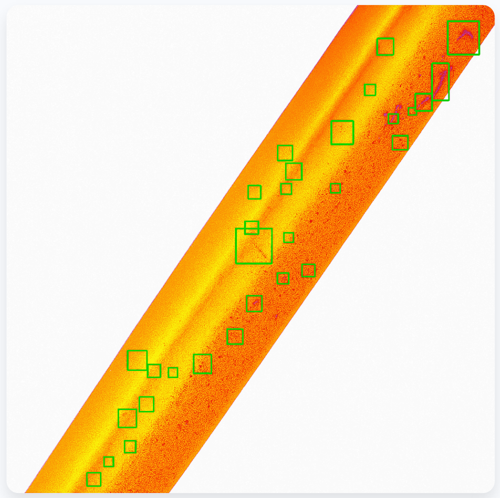
+2.2% mAP

RGB Image



Visibility hampered by shadows

Fused Image

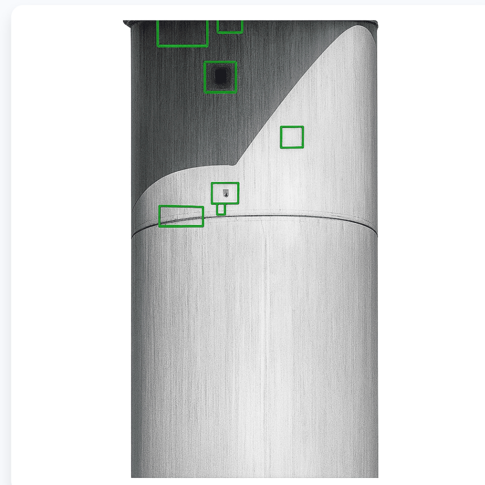


Enhanced fracture line contrast

Tower Corrosion

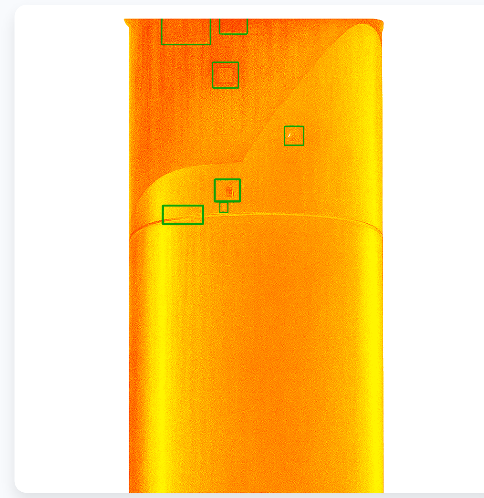
+2.0% mAP

RGB Image



Subtle surface degradation

Fused Image

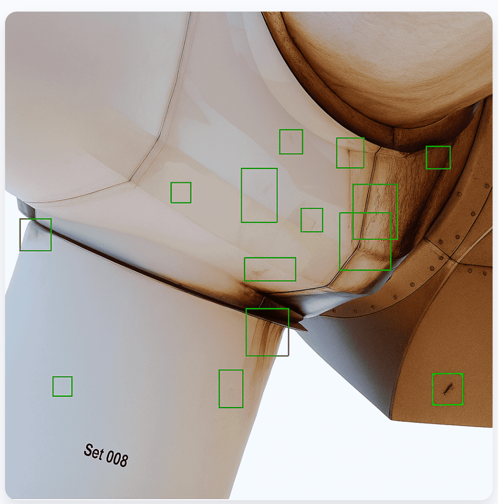


Distinct corrosion patterns

Rotor Stress

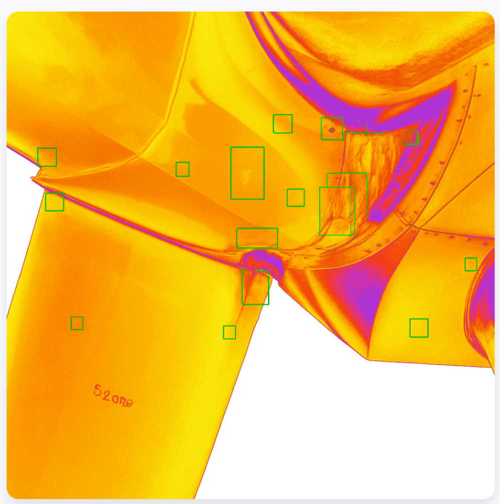
+3.0% mAP

RGB Image



No visible stress indicators

Fused Image

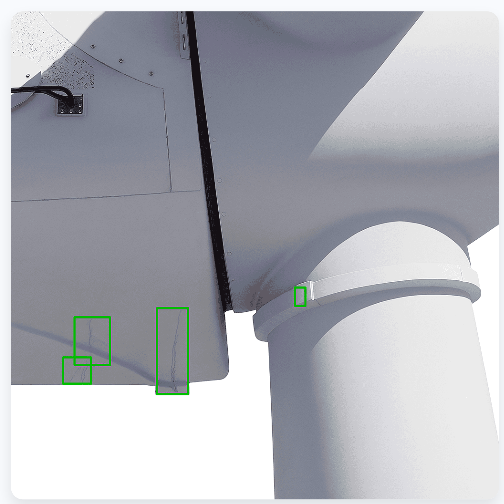


Thermal stress patterns revealed

Motor Overheating

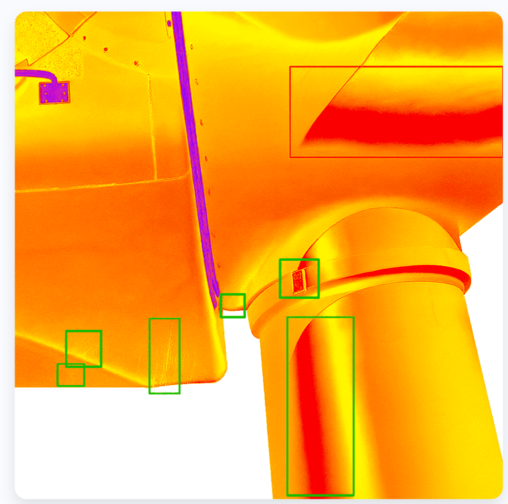
+3.4% mAP

RGB Image



No visible damage signs

Fused Image



Critical thermal hotspots visible

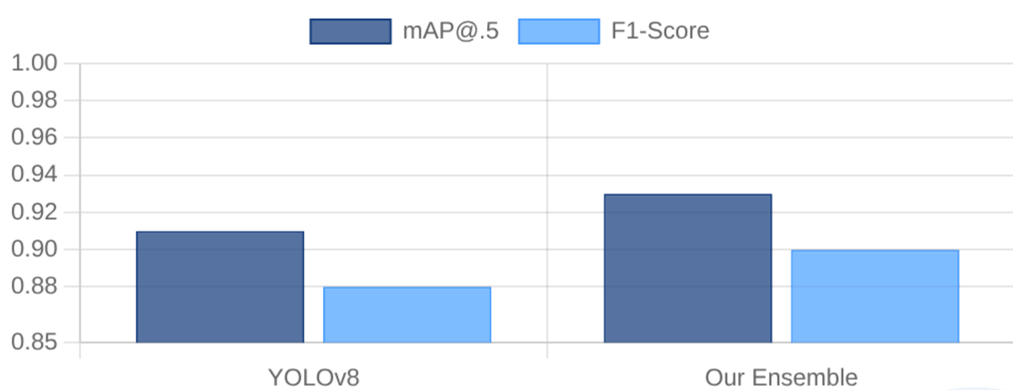
Key Observations

- **Enhanced contrast** improves surface defect detection
- **Thermal anomalies** invisible in RGB revealed
- **Critical defects** missed by visual inspection detected

Conclusion and Future Work

Key Findings

- **mAP@.5: 0.93** | **F1-score: 0.90**
- **+2.2%** improvement over single YOLOv8
- Superior **thermal defect** detection
- Enhanced **subtle cracks** & **corrosion** visibility



Advantages

- **Multi-modal synergy** for comprehensive diagnostics
- **Speed** of single-stage + **precision** of specialist model
- Reduces **false negatives** & **false positives**
- Addresses **single-spectral limitations**

Future Research

- **Edge deployment** optimization for UAVs
- **Robust sensor fusion** algorithms
- **Environmental noise** reduction
- **Hyperspectral imaging** integration

0.93	0.90	+2.2%	3
mAP@.5	F1-Score	Improvement	Defect Types