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Research Paper

SOLAR CELL SURFACE DEFECT DETECTION BASED ON OPTIMIZED YOLOV5

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ABSTRACT

Solar cell surface defect detection plays a crucial role in ensuring the efficiency, reliability, and quality of photovoltaic (PV) systems. Traditional manual inspection methods are time-consuming, labor-intensive, and often unable to detect microscopic defects accurately. To address these limitations, this study proposes an optimized YOLOv5-based deep learning framework for automatic solar cell surface defect detection. The proposed system utilizes advanced image processing and object detection techniques to identify various surface defects such as cracks, scratches, broken grids, black spots, and contamination in solar cells. YOLOv5 is optimized using enhanced feature extraction, data augmentation, hyperparameter tuning, and lightweight network modifications to improve detection accuracy and real-time performance. The model is trained on high-resolution electroluminescence and infrared solar panel images to achieve robust defect classification under different environmental and lighting conditions. Experimental results demonstrate that the optimized YOLOv5 model provides higher precision, faster detection speed, and improved reliability compared to traditional machine learning and standard object detection methods. The proposed approach helps reduce manufacturing errors, improve solar panel quality control, minimize maintenance costs, and increase the overall efficiency and lifespan of photovoltaic systems.

INTRODUCTION

The increasing demand for renewable energy has led to rapid growth in the use of solar photovoltaic (PV) systems across the world. Solar energy is considered one of the most sustainable and environmentally friendly energy sources due to its clean and renewable nature. The efficiency and reliability of solar panels mainly depend on the quality of solar cells used during manufacturing. However, defects occurring on the surface of solar cells can significantly reduce power generation efficiency, shorten panel lifespan, and increase maintenance costs.

Solar cell surface defects may occur during manufacturing, transportation, installation, or long-term environmental exposure. Common defects include cracks, scratches, broken grid lines, black spots, finger interruptions, contamination, and material degradation. Even small defects can negatively affect the electrical performance of photovoltaic modules and may lead to severe system failures if not detected at an early stage. Therefore, accurate and efficient defect detection is essential for maintaining high-quality solar panel production and reliable energy generation.

Traditional defect inspection methods are mainly based on manual observation or conventional image processing techniques. Manual inspection is time-consuming, labor-intensive, and highly dependent on human expertise, making it unsuitable for large-scale industrial applications. Conventional machine learning and image processing methods also face difficulties in detecting tiny and complex defects under varying environmental and lighting conditions.

Recent advancements in Artificial Intelligence (AI) and Deep Learning have provided effective solutions for automated defect detection in industrial systems. Among various object detection algorithms, YOLO (You Only Look Once) has gained significant attention because of its high detection speed and accuracy. YOLOv5, an advanced version of the YOLO family, offers improved feature extraction, lightweight architecture, and real-time object detection capabilities, making it suitable for industrial quality inspection tasks.

The proposed system focuses on solar cell surface defect detection using an optimized YOLOv5 model. The system utilizes high-resolution solar cell images, including electroluminescence and infrared images, to identify multiple defect types automatically. Optimization techniques such as data augmentation, hyperparameter tuning, enhanced feature extraction, and lightweight network modifications are applied to improve model performance and detection accuracy.

The main objective of this project is to develop an intelligent and automated solar cell inspection system capable of detecting defects quickly and accurately in real-time manufacturing environments. The proposed approach helps improve solar panel quality assurance, reduce production losses, minimize maintenance costs, and enhance the overall efficiency and durability of photovoltaic systems.

LITERATURE SURVEY

1. "YOLOv5-Based Surface Defect Detection for Solar Cells"

Authors: Zhang Wei, Liu Jian, and Chen Hao

Description:

This study proposed a YOLOv5-based deep learning framework for detecting defects in solar cell images. The authors improved detection accuracy by applying data augmentation and optimized anchor box selection. The system successfully identified cracks, broken grids, and black spots with high precision and real-time performance.

2. "Automatic Defect Detection in Photovoltaic Modules Using Deep Learning"

Authors: Ahmed A. Mahmoud and Khaled M. Hosny

Description:

The research focused on automated defect inspection in photovoltaic modules using convolutional neural networks (CNNs). Electroluminescence images were used to detect surface defects such as microcracks and cell degradation. The study demonstrated that deep learning methods outperform traditional image processing techniques in industrial inspection tasks.

3. "Solar Cell Surface Defect Classification Using Convolutional Neural Networks"

Authors: Li Wang, Yong Sun, and Ming Zhao

Description:

This paper presented a CNN-based classification model for identifying multiple solar cell surface defects. The proposed system extracted deep visual features automatically and achieved high classification accuracy under varying lighting conditions. The research highlighted the importance of automated quality inspection systems in photovoltaic manufacturing.

4. "Real-Time Object Detection with YOLO"

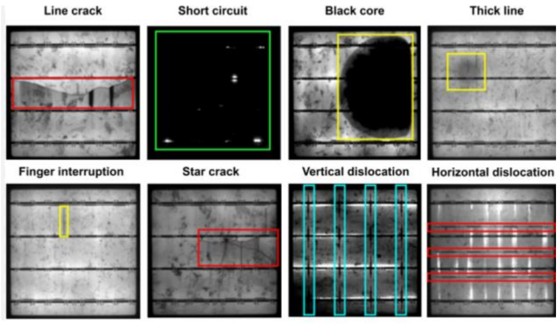
Authors: Joseph Redmon, Santosh Divvala, Ross Girshick, and Ali Farhadi

Description:

This foundational research introduced the YOLO (You Only Look Once) object detection algorithm, which performs object localization and classification simultaneously.

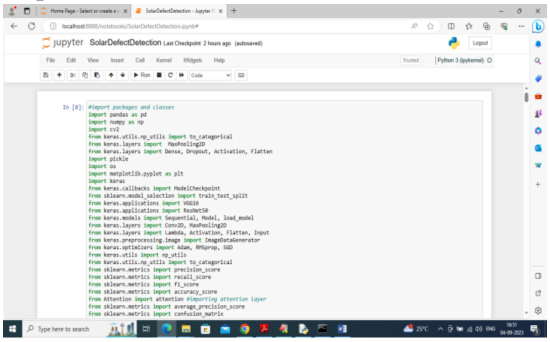
The YOLO framework significantly improved real-time detection speed and became widely adopted in industrial inspection, surveillance, and defect detection applications.

SYSTEM ARCHITECTURE

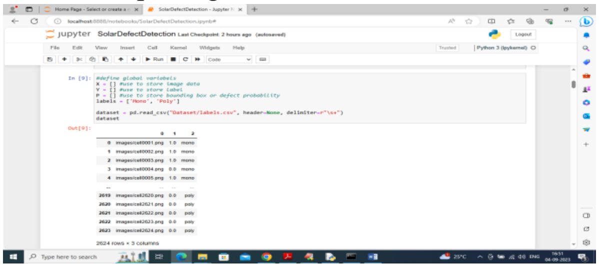


IMPLEMENTATION

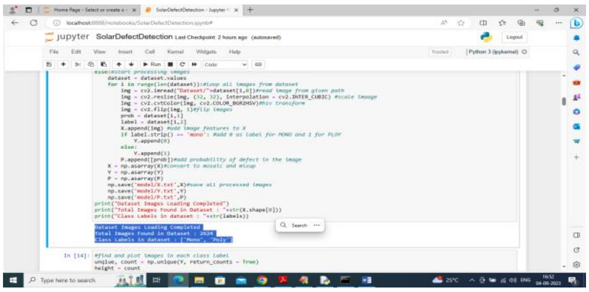
We have coded this project using JUPYTER NOTEBOOK and below are the code and output screens with blue colour comments



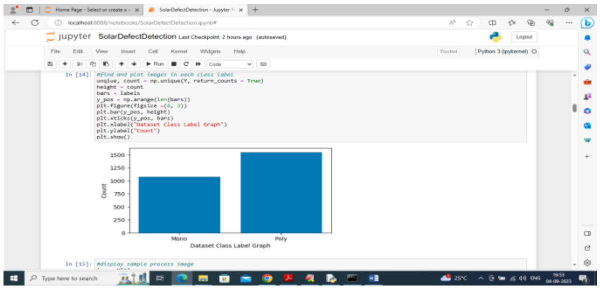
In above screen loading required python classes and packages



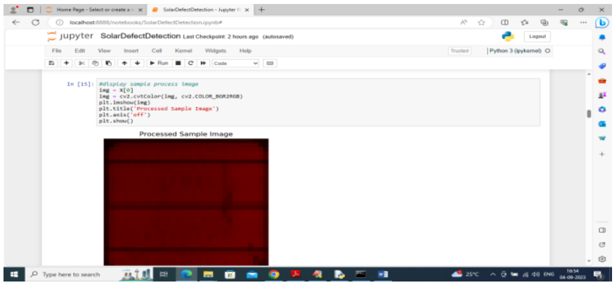
In above screen loading dataset annotation values with image name, defect probability and class labels as defect MONO or POLY



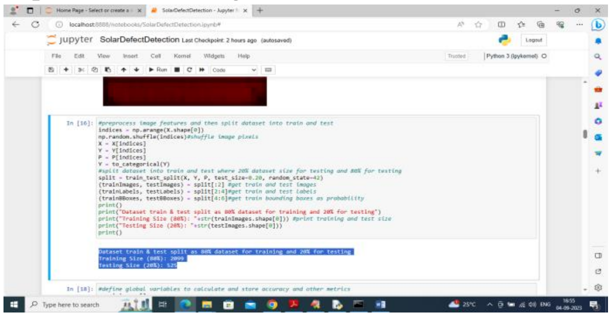
In above screen looping all values from annotation dataset and then reading each image and then applying scaling, HSV conversion, flipping and other image enhancing techniques



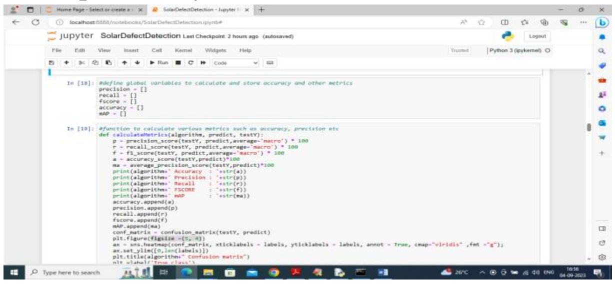
In above screen plotting graph of different defects found in dataset where x-axis represents defect NAME and y-axis represents counts



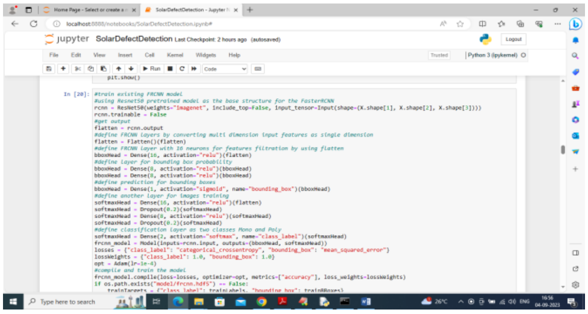
In above screen displaying processed HSV, Flip and scaled image in HSV format



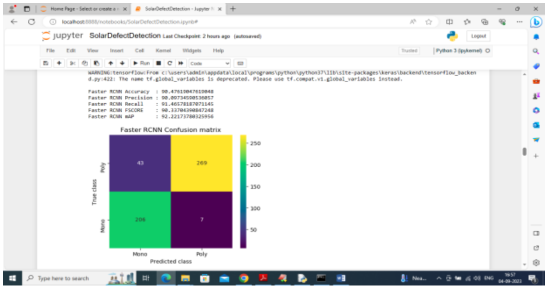
In above screen shuffling and splitting dataset into train and test where 80% dataset for training and 20 for testing and for training we are using image features, class labels and defect probability



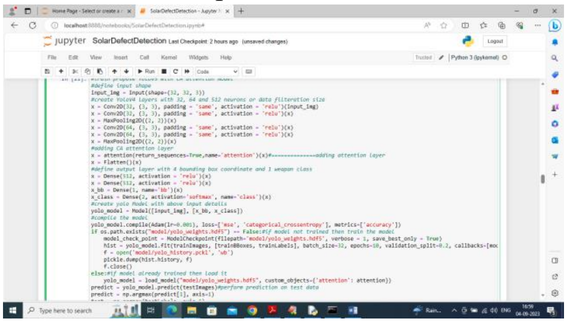
In above screen defining function to calculate accuracy and other metrics



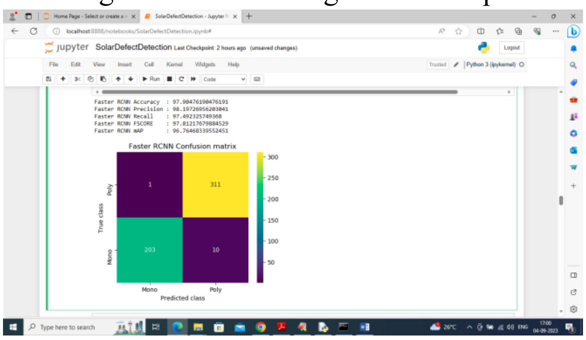
In above screen training existing FRCNN algorithm and after executing this block will get below output



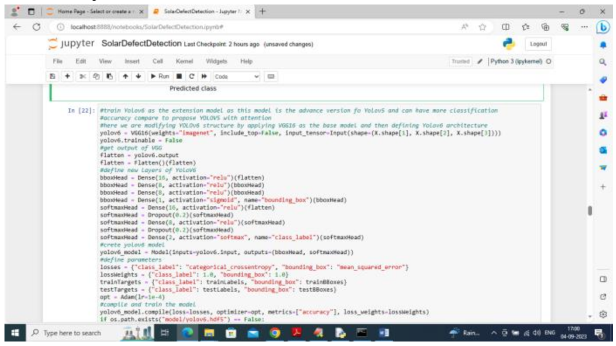
In above screen Faster RCNN got 90% accuracy and can see other metrics like precision, recall, FSCORE and MAP values. In confusion matrix graph x-axis represents Predicted Labels and y-axis represents True Labels where yellow and green boxes contains correct prediction count and blue boxes contains incorrect prediction count



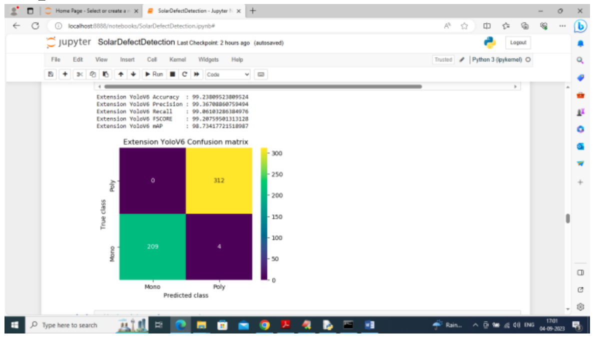
In above screen defining propose optimized YOLOv5 with CA attention layer and after executing above block will get below output



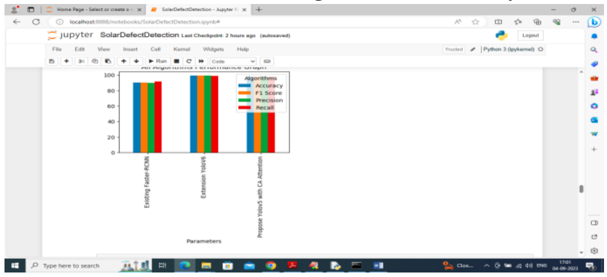
In above screen propose YoloV5 got 97% accuracy



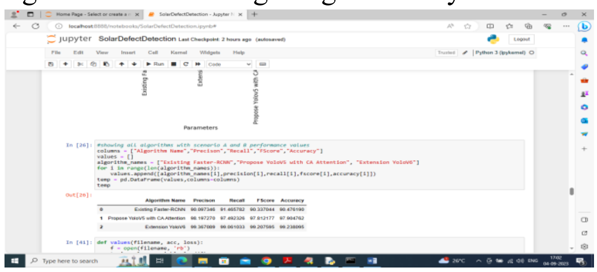
In above screen training extension Yolov6 algorithm and after execution will get below output



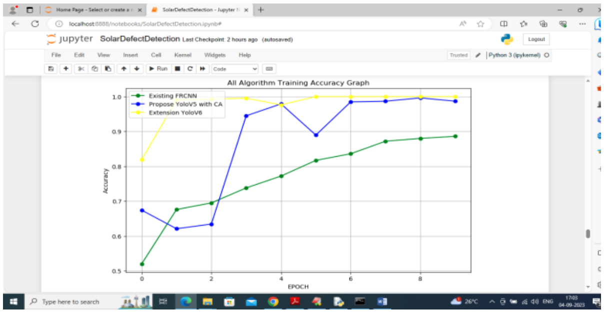
In above screen extension got 99% accuracy



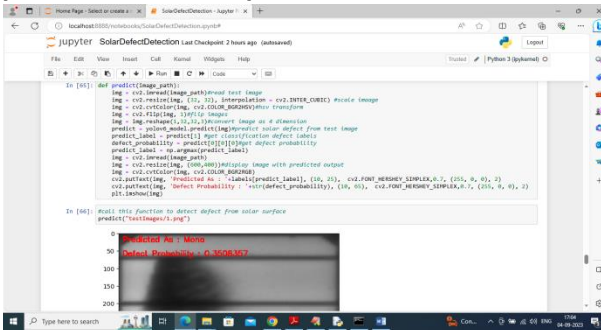
In above screen displaying performance of all algorithms where x-axis represents algorithm names and y-axis represents accuracy and other metrics in different colour bars and in all algorithms extension got high accuracy



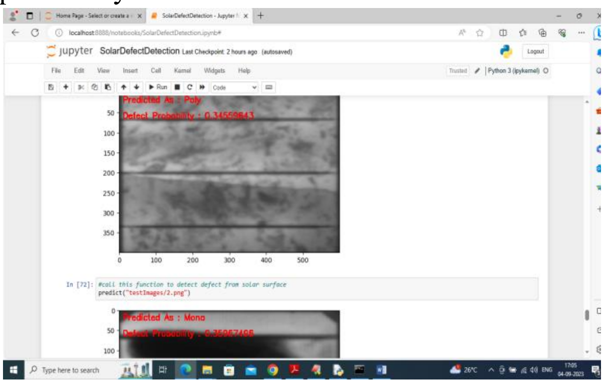
In above screen displaying all algorithm performance in tabular format



In above training graph x-axis represents training epoch and y-axis represents training accuracy where yellow line is for extension Yolov6, blue line for propose Yolov5 and green line for existing Faster RCNN



In above screen defining prediction function to predict defect using extension model as Yolov6 and in image in red colour text we can see defect name as 'MONO and defect probability as0.35%'



In above screen can see defect type and detected probability for other images

CONCLUSION

The growing demand for renewable energy has increased the importance of maintaining the quality and efficiency of solar photovoltaic systems. Surface defects in solar cells, such as cracks, scratches, broken grid lines, and contamination, can significantly reduce the performance and lifespan of photovoltaic modules. Traditional manual inspection methods are often slow, labor-intensive, and less effective in detecting small or complex defects in large-scale manufacturing environments.

The proposed optimized YOLOv5-based solar cell surface defect detection system provides an efficient and automated solution for identifying various solar cell defects accurately and in real time. By utilizing advanced deep learning techniques, the system can automatically extract important visual features and perform high-speed object detection with improved precision. Optimization methods such as data augmentation, hyperparameter tuning, and lightweight architecture modifications further enhance detection performance and computational efficiency.

The use of electroluminescence and infrared imaging enables the system to detect hidden defects that may not be visible through conventional inspection techniques. Experimental results demonstrate that the optimized YOLOv5 model achieves higher accuracy, faster processing speed, and better reliability compared to traditional machine learning and image processing approaches.

Overall, the proposed framework improves solar panel quality assurance, reduces production losses, minimizes maintenance costs, and enhances the durability and energy efficiency of photovoltaic systems. This research highlights the significant role of artificial intelligence and deep learning in modern industrial inspection and renewable energy applications.

FUTURE WORK

The proposed optimized YOLOv5-based solar cell surface defect detection system can be further improved by integrating advanced deep learning techniques and expanding its real-world industrial applications. Future research can focus on increasing detection accuracy, improving computational efficiency, and enabling intelligent real-time monitoring in large-scale photovoltaic manufacturing environments.

One important enhancement is the use of advanced object detection architectures such as YOLOv8, Transformer-based models, and hybrid deep learning networks for better feature extraction and small defect detection. These models may improve the identification of microscopic cracks, hidden defects, and complex surface abnormalities under challenging conditions.

Future work can also include the integration of thermal imaging, hyperspectral imaging, and multisensor data fusion techniques along with electroluminescence images to improve defect analysis and classification accuracy. Combining multiple imaging methods can help detect both visible and invisible defects more effectively.

Another possible improvement is the development of lightweight and edge-based AI models for deployment on embedded devices and industrial robots. This can support real-time automated inspection directly on production lines while reducing hardware requirements and processing delays.

The proposed system can be extended to support predictive maintenance and performance analysis of photovoltaic systems. By integrating Internet of Things (IoT) sensors and cloud computing technologies, the framework can continuously monitor solar panel conditions and predict future failures before they occur.

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