Autonomous Solar Panel Cleaning with Deep Reinforcement Learning

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# 1. Introduction

Background:  
Solar panels lose efficiency due to dust and dirt accumulation, especially in high-pollution or desert areas. Manual cleaning is not only costly and inefficient but also poses a safety risk in large-scale solar farms. Automation is crucial for sustainable, scalable maintenance.  
  
Problem Statement:  
Manual solar panel cleaning is labor-intensive and inefficient. The goal is to build a robot that autonomously identifies dusty areas and cleans only those, reducing energy and water consumption.  
  
Project Aim:  
To develop an autonomous robot equipped with YOLOv11s for dust detection and Q-learning for movement planning, optimized for minimal cleaning effort and maximum efficiency.

# 2. Objectives & Highlights

## Objectives

- Develop an autonomous solar panel cleaning robot.

- Use YOLOv11s for real-time dust detection.

- Implement Q-learning for smart movement.

- Clean only dirty sections to conserve resources.

- Integrate IR sensors for edge detection and safety.

## Key Highlights

- Model Used: YOLOv11s (custom-trained for dust detection)  
- Reinforcement Learning: Q-learning for movement and cleaning decisions  
- Edge Safety: IR sensors to detect panel boundaries  
- Microcontroller: Raspberry Pi 4 (8GB)  
- Components: 4 DC motors, camera, motor driver, FET control for cleaner  
- Detection Accuracy: ~80% on test data  
- Cleaning Optimization: Short forward/backward bursts to reduce drift  
- Real-Time Execution: Via Python, OpenCV, and GPIO control

# 3. System Architecture & Workflow

## Workflow Description

1. Initialization: System boots, calibrates MPU6050, and camera starts.  
2. Dust-Free Image Capture: A clean panel image is captured initially for baseline comparison.  
3. Movement Strategy: Robot moves in a zigzag path across the panel, checking for dirt.  
4. Dust Detection: Camera frames are passed to YOLOv11s.  
5. Action Decision (Q-learning):  
 - If dust is detected → Activate FET circuit and clean  
 - If no dust → Move to next section  
6. Safety: IR sensors stop robot at edges; it reverses and turns to next row.

## Mathematical Model (Q-Learning)

Q(s, a) ← Q(s, a) + α [r + γ max Q(s', a') - Q(s, a)]

# 4. Tools, Implementation & Results

## Tools & Technologies Used

- Python – Main programming language  
- OpenCV – Image preprocessing and visualization  
- YOLOv11s – Custom-trained dust detection model  
- Google Colab – Model training and evaluation  
- Raspberry Pi 4 (8GB) – Onboard control and computation  
- MPU6050 – For angular orientation (used during turns)  
- IR Sensors – For edge detection  
- Motor Driver (L298N) – For DC motor control  
- FET Switch – For activating cleaner (spray/sweep)

## Final Results

- Detection Accuracy: ~80%  
- Cleaning Coverage Efficiency: 90–95%  
- Energy & Water Savings: Cleans only where needed  
- Safety: IR-based edge detection avoids falls  
- Zigzag Pattern Movement: Achieved using orientation control via MPU6050  
- Live Display: Camera feed with dust box overlay and detection confidence

# 5. Conclusion & Future Work

## Conclusion

The system effectively detects and cleans dusty solar panel areas using deep reinforcement learning. Real-time object detection via YOLOv11s and path planning via Q-learning resulted in optimized cleaning with minimal resource use. The project showcases a fully functional prototype deployable in real-world solar farms.

## Future Improvements

- Add solar-powered recharging for complete autonomy  
- Integrate GUI for remote control and diagnostics  
- Upgrade model for multi-class dust types  
- Improve angular precision in edge turning  
- Add water recycling and autonomous docking/charging