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**Implementasi Two-Stage Detection YOLOv11 pada Sistem Robot Pembersih Panel Surya Otonom Berbasis
Klasifikasi Tingkat Kekotoran**
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INTISARI

IMPLEMENTASI *TWO-STAGE DETECTION* YOLOv11 PADA SISTEM ROBOT PEMBERSIH PANEL SURYA OTONOM BERBASIS KLASIFIKASI TINGKAT KEKOTORAN

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Akumulasi debu pada panel surya menurunkan efisiensi konversi energi, sementara metode konvensional berbasis sensor *Light Dependent Resistor* (LDR) atau sensor arus tidak dapat membedakan kotoran dari gangguan cuaca, dan sistem berbasis *cloud* rentan gagal koneksi di lokasi terpencil. Penelitian ini merancang robot pembersih panel surya otonom yang memadukan deteksi visual *two-stage* YOLOv11, kendali *Proportional-Integral-Derivative* (PID) *closed-loop*, dan komunikasi serial lokal agar mandiri pada Pembangkit Listrik Tenaga Surya (PLTS) *off-grid* tanpa internet.

Sistem menggunakan arsitektur *two-tier*: Raspberry Pi 5 menjalankan *pipeline two-stage detection* (deteksi panel YOLOv11n, klasifikasi tingkat kekotoran YOLOv11n-cls ke empat kelas: bersih, ringan, sedang, berat) yang dikonversi menjadi *weighted score* untuk strategi pembersihan adaptif, sedangkan ESP32 mengeksekusi siklus pembersihan melalui *finite state machine* berkendali PID dengan umpan balik *rotary encoder* dan kompensasi *feedforward*. Kedua unit berkomunikasi via UART kabel langsung, dan hasil pembersihan diverifikasi otomatis melalui deteksi ulang.

Model deteksi panel mencapai mAP@0.5 99,43% (*precision* 97,58%, *recall* 99,46%) dan model klasifikasi mencapai akurasi 98,00% (450 sampel validasi), sementara validasi lapangan (60 sampel) mencapai 96,67%. Inferensi *two-stage* 494,77 ms/*frame* (2,02 FPS); kendali PID dengan *feedforward* menjaga *overshoot* di bawah 10% dan galat tunak dalam *deadband* 0,5 RPM meski beban gesek bervariasi; komunikasi UART mencapai *success rate* 100% dengan latensi rata-rata 52,49 ms. Sistem berhasil menjalankan siklus pembersihan adaptif tiga level dengan verifikasi otomatis, layak diterapkan pada PLTS *off-grid*.

Kata kunci: panel surya, YOLOv11, *two-stage detection*, kendali PID, robot otonom, *edge computing*

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ABSTRACT

IMPLEMENTATION OF YOLOv11 TWO-STAGE DETECTION IN AUTONOMOUS SOLAR PANEL CLEANING ROBOT BASED ON DIRT LEVEL CLASSIFICATION

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Dust accumulation on solar panel surfaces reduces energy conversion efficiency, while conventional methods based on LDR or current sensors cannot visually distinguish soiling from weather disturbances, and cloud-based systems are prone to connection failures in remote locations. This research designs an autonomous solar panel cleaning robot integrating YOLOv11 two-stage visual detection, closed-loop PID control, and local serial communication for independent operation on off-grid solar power plants (PLTS) without relying on the internet.

The system uses a two-tier architecture: a Raspberry Pi 5 runs the two-stage detection pipeline (panel detection with YOLOv11n, dirt-level classification with YOLOv11n-cls into four classes: clean, light, moderate, heavy) converted into a weighted score for adaptive cleaning strategy, while an ESP32 executes the cleaning cycle via a finite state machine with PID control using rotary encoder feedback and feedforward compensation. The units communicate via direct wired UART, with cleaning outcomes automatically verified through re-detection.

The panel detection model achieves mAP@0.5 of 99.43% (precision 97.58%, recall 99.46%) and the classification model reaches 98.00% accuracy (450 validation samples), while field validation (60 samples) obtained 96.67% accuracy. Two-stage inference takes 494.77 ms per frame (2.02 FPS); PID control with feedforward keeps overshoot below 10% and steady-state error within a 0.5 RPM deadband despite varying friction loads; UART communication achieves a 100% success rate with 52.49 ms average latency. The system successfully performs adaptive three-level cleaning with automatic verification, suitable for off-grid solar power plant installations.

Key words: solar panel, YOLOv11, two-stage detection, PID control, autonomous robot, edge computing