Autonomous PV Fault Detection and Hardware Isolation System for 3U CubeSats

Abstract – This paper presents an autonomous AI-powered protection system for CubeSat Electrical Power Systems using dual-layer hardware comparators and Random Forest machine learning. The system combines always-on hardware protection (Layer 1) with AI-gated adaptive comparators (Layer 2) to prevent solar panel failures. Trained on NEPALISAT-1 telemetry and validated cross-satellite on RAAVANA, the solution achieves 98.6% prediction accuracy with 157s inference time and hardware response under 1s. The design fits within 3U CubeSat constraints, consuming <180mW power.

1 Introduction and Mission Overview

This project develops an autonomous protection system for CubeSat Electrical Power Systems (EPS) that operates independently of ground control. The hybrid AI-electronics architecture addresses the critical need for fault prevention during communication blackouts. The system achieves three key objectives:

1. Near-future solar panel power prediction via Random Forest models
2. Detection of anomaly patterns indicating short-circuit risks or power collapse
3. Dual-layer hardware protection with AI-gated activation

2 Subsystem Analysis

2.1 Electrical Power System Risk Assessment

The primary risks addressed include short circuits, hot spots, and panel delamination that can cause rapid EPS destabilization. Historical data from NEPALISAT-1 shows these faults can propagate within microseconds, necessitating sub-second autonomous response.

2.2 Failure Mode Analysis

- **False Positive Mitigation:** Multi-condition voting (2/4 conditions required) prevents unnecessary trips during eclipse transitions and attitude maneuvers
- **Fault Signature Coverage:** Hardware thresholds catch both instantaneous spikes (Layer 1) and gradual degradation (Layer 2)

3 System Architecture

3.1 Dual-Layer Protection Approach

The architecture implements a dual-layer protection strategy with strict functional separation:

- **Layer 1 (Always-On):** Hardware comparators with 0V threshold, responding in $<1\mu s$ to catastrophic faults
- **Layer 2 (AI-Gated):** Adaptive comparators with 1200mV, 2000mV, 3000mV, 50mA threshold, enabled by MCU upon anomaly detection
- **AI/MCU Role:** Random Forest-based anomaly prediction and noise filtering, reducing false positives from shadowing events

Key Innovation: Combines AI-driven pre-failure detection with hardware-level reliability, maintaining protection during MCU failures through independent comparator operation.

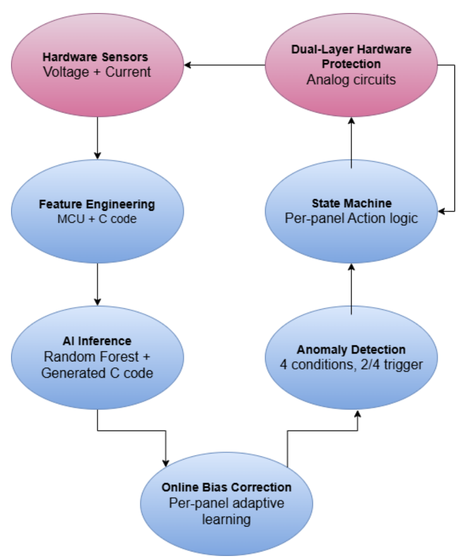

Figure 1: Integrated AI-Hardware Protection Workflow for CubeSat Solar Panels

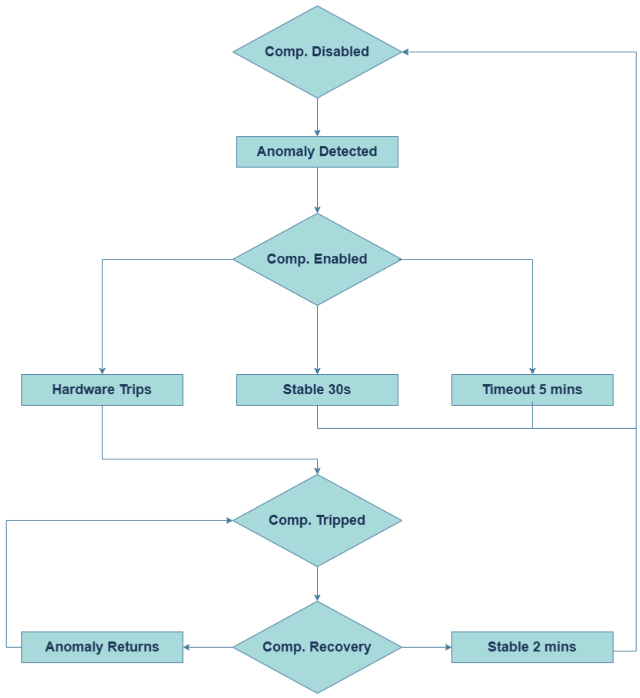

Figure 2: State machine Logic

3.2 Hardware Implementation

The system protects 13 solar panels, each with two series-connected cells in parallel configuration. Per-panel hardware includes:

- **Sensors:** Voltage monitoring, INA219 current sensors, temperature sensors
- **Protection:** LM339 comparators (Layer 1 + Layer 2), 74HC32 OR gate
- **Actuation:** Si2301 P-channel MOSFET for physical isolation
- **Processing:** STM32L496ZGTx MCU for AI inference and system management

The hardware comparators operate independently of the MCU, which only controls Layer 2 arming while Layer 1 provides always-on protection.

4 Implementation Details

4.1 Electronic Protection Circuit

The dual-layer protection circuit ensures fail-safe operation:

- **Layer 1 Threshold:** 0v
- **Layer 2 Threshold:** 1200mV, 2000mV, 3000mV, 50mA when armed by AI
- **MOSFET Control:** OR-gated comparator outputs ensure either layer can isolate panels

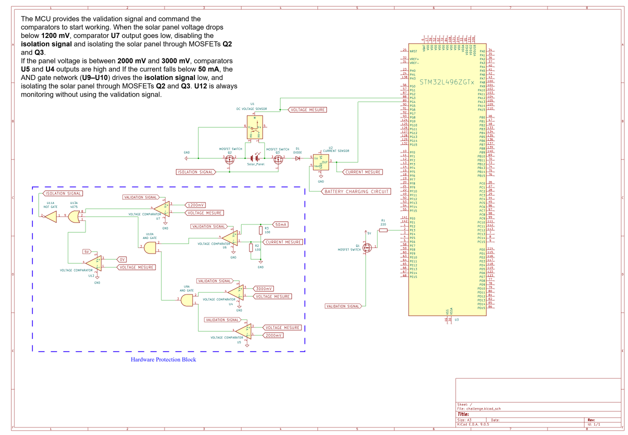

Figure 3: Electronic Protection Circuit

4.2 AI Model Development

The system employs Random Forest models trained on 5-second cadence telemetry:

- **Target Variables:** Power ($P = V \cdot I$) and voltage prediction
- **Features:** Raw V, P data plus derivatives (dP/dt, dV/dt)
- **Performance:** 98.6% accuracy (MAE=0.034W) with 157μs inference time
- **Deployment:** Models transpiled to C using m2cgen for STM32 integration

4.3 Fault Detection Logic

The MCU executes continuous monitoring with four detection conditions:

1. Power spike: $P_{pred} > 1.2 \times P_{nominal}$
2. Voltage drop: $V_{measured} < V_{pred} - 1.0V$
3. High dynamics: $|dP/dt| > 2.0 \wedge |dV/dt| > 0.5$
4. Large residual: $|P_{measured} - P_{pred}| > 3\sigma$

Layer 2 arming requires 2+ conditions true. Online bias correction adapts to radiation degradation using exponential weighted moving average ($\alpha = 0.01$).

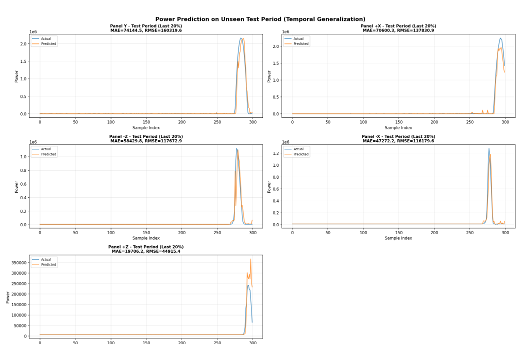

Figure 4: Real-time Power Prediction on other models

5 Validation and Testing

5.1 Cross-Satellite Validation

The system was rigorously validated:

- **Training:** NEPALISAT-1 data (5 panels, 10,000+ samples)
- **Cross-Panel:** Model generalization across different panel orientations
- **Cross-Satellite:** Transfer learning to RAAVANA data (MAE=0.08W without retraining)
- **Fault Injection:** Short circuit, shading, and noise scenarios tested

5.2 Performance Metrics

Key performance achievements:

- **Detection Time:** 5-10s (Layer 2), <1μs (Layer 1)
- **Accuracy:** 98.6% prediction, <1% false positive rate
- **Resource Usage:** 190KB Flash, 1.7KB RAM, <180mW power

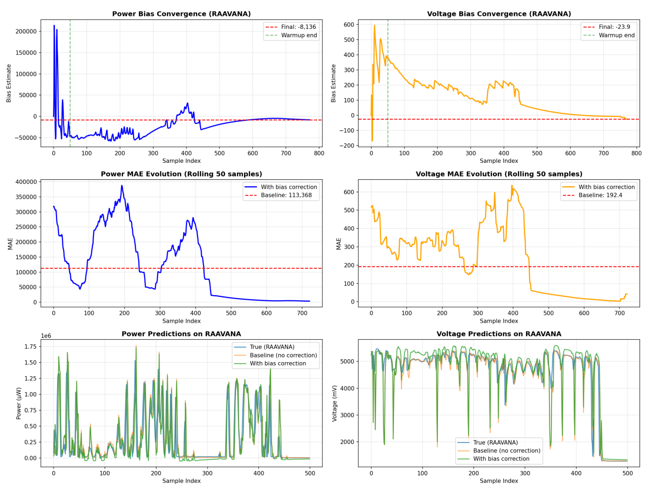

Figure 5: Convergence of the model on other cubesats

5.3 Matlab Simulation

This simulation models a CubeSat operating in Low Earth Orbit to generate realistic solar cell performance data under dynamic illumination conditions.

The workflow leverages **MATLAB** and **Simulink** for high-fidelity, physics-based modeling: the **asbCubeSat** model computes the satellite's orbital parameters and Sun incidence angles, which are then translated into panel irradiance profiles using the **Satellite Toolbox**.

These inputs drive a detailed **GaAs solar cell model** ($I_{sc} = 1$ A, $V_{oc} = 2$ V) implemented with **Simscape Electrical**, enabling accurate estimation of voltage, current, and power characteristics.

The MATLAB–Simulink environment provides integrated visualization, parametric control, and data export capabilities, making it well-suited for developing, validating, and analyzing satellite power systems with or without added stochastic noise for inference or fault-detection testing.

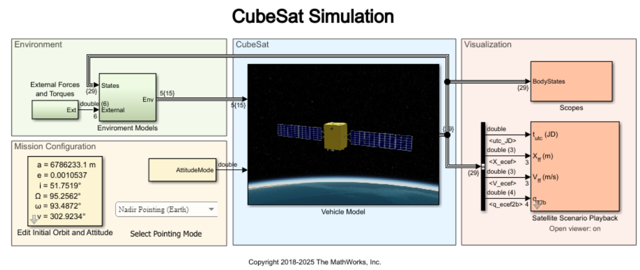

Figure 6: CubeSat MATLAB/Simulink Simulation

6 Conclusion and Future Work

The dual-layer AI-hardware protection system demonstrates reliable autonomous fault prevention for CubeSat EPS.This hybrid approach has promising potential on other subsystems. Key advantages include:

- Fail-safe operation through independent hardware protection
- Intelligent false positive reduction via AI filtering
- Proven cross-satellite generalization capability
- Minimal resource footprint suitable for 3U CubeSats

Future work will focus on radiation-hardened implementations, extended validation with additional satellite platforms, and integration with CubeSat bus standards for broader deployment and combining AI algorithms with continous monitoring using electronics in other systems.