An Integrated Electrical–Mechanical Capstone Platform for Solar Panel Maintenance with Automated Cleaning and Inspection

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Abstract

This paper presents an interdisciplinary, project-centered capstone platform for solar panel maintenance with a primary emphasis on electrical system design and integration. Supported by a SUNY (State University of New York) Innovative Instruction Technology Grant (IITG 2025–26) and school funding, totaling approximately $40,000, the project engages undergraduate students in developing an automated inspection and cleaning system that combines a land-based robotic platform, embedded control hardware, and AI-assisted perception. Electrical Engineering Technology students led the design and validation of power distribution and protection, motor driver control, embedded communication, and system safety, while collaborating with mechanical and computing teams. The platform is embedded across sequential Electrical Senior Design courses and evaluated using course-embedded rubrics and system-level validation milestones aligned with ABET outcomes. Prototype testing demonstrated stable power delivery, reliable wireless control, and repeatable actuator performance, providing evidence of both technical robustness and instructional effectiveness.

1. Introduction

The increasing deployment of solar panels, a central component of photovoltaic energy systems, has highlighted the need for effective maintenance strategies to address dust accumulation, performance degradation, and routine fault detection [1], [2]. Addressing these challenges requires engineers who can integrate power electronics, embedded control, robotics, and data-driven decision-making into cohesive systems. To meet this need, an interdisciplinary instructional platform was developed to embed AI-driven robotics for solar-panel inspection and cleaning into senior-level engineering coursework.

Prior work in autonomous control of complex energy systems provides a foundation for integrating AI-supported control strategies into applied engineering education. These studies have shown that distributed, agent-based control architectures can support scalable and deterministic coordination of power electronic converters in complex energy systems [3], [4]. Communication among multi-agent systems and their design algorithms determines the speed of convergence among agents [5].

The project, titled AI-Driven Robotics for Solar Energy Maintenance: An Interdisciplinary Approach to Education and Sustainability, was implemented across Electrical Engineering Technology and Electrical Senior Design courses, with related AI content introduced to Computer Information Systems (CIS) students through an AI Essentials course. For the mechanical component, a group of students from the Mechanical Engineering Technology

(MET) program participated through a Mechanical Senior Design course. The Electrical Engineering Technology (EET) team includes 3 senior students who started in June 2025 as interns and continued work in Electrical Design I & II courses. The Mechanical group changed over two semesters, since the Mechanical Senior Design course is only one semester long. However, every semester, 4 MET students were working on the project. Additionally, a senior Mechanical student began the project's design and implementation in the summer. In the CIS program, 3 students were working from Fall 2025 through the end of Spring 2026. Although EET and MET students are all seniors within the top 10 percent of their classes, CIS students are still sophomores. They have mostly been learning, and they can continue working on this project or a similar one. Students in each disciplinary area were advised by faculty members with corresponding technical expertise and engaged in the end-to-end design of an automated solar maintenance platform, including a land-based robot (LandBot), an aerial drone, robotic arms, and a sample-sized photovoltaic panel within a multidisciplinary capstone framework. The collaboration among 5 advisors and 10 students was challenging, but the group eventually developed rules to manage the project efficiently.

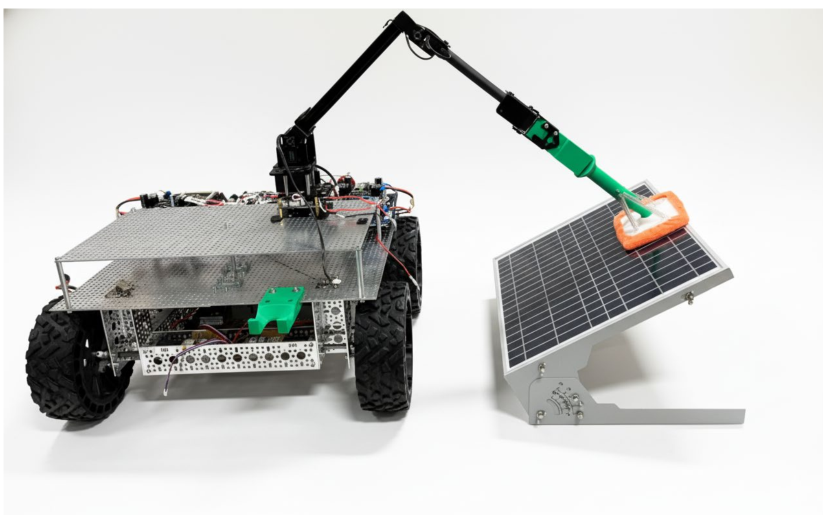

Figure 1 shows the experimental prototype developed for the interdisciplinary capstone platform. The prototype consists of a land-based robotic vehicle with a multi-degree-of-freedom arm interacting with a mock-up of an inclined photovoltaic panel.

The system integrates electrical power distribution, embedded control hardware, motor drivers, and wireless communication on a modular chassis, allowing students to validate coordinated motor control and power management under dynamic loading conditions. The completed prototype is shown in Figure 1. Students entered the project with prior curricular exposure to embedded systems and microcontroller programming [6], [7]. This physical configuration supports hands-on exploration of system-level electrical and mechanical integration relevant to renewable energy maintenance applications. The platform consists of a robotic system with a multi-degree-of-freedom arm, coordinated with an aerial drone, for inspection tasks. While the overall system is interdisciplinary, this paper emphasizes the electrical engineering contributions, including power distribution and protection, motor control, embedded communication, and safety-critical system integration.

In addition to technical development, the project incorporates a structured evaluation framework using rubric-based assessment, system validation milestones, and faculty review to measure student learning and instructional effectiveness. This combination of authentic system testing and course-embedded assessment provides a reproducible model for project-centered electrical engineering education.

2. System-Level Architecture and Multi-Domain Interaction

Figure 2 illustrates the electrical system decomposition and the control hierarchy used in the platform. Tier 1 represents the centralized control level that communicates directly with major system modules. Tier 2 shows the distributed control when the Drone and LandBot exchange data directly. In Tier 3, the local controllers are used for the components. At the lower level, power is distributed to system modules, including the LandBot, the primary four-wheeled exploratory ground robot. For clarity, this article refers to the land-based robotic vehicle as the LandBot.

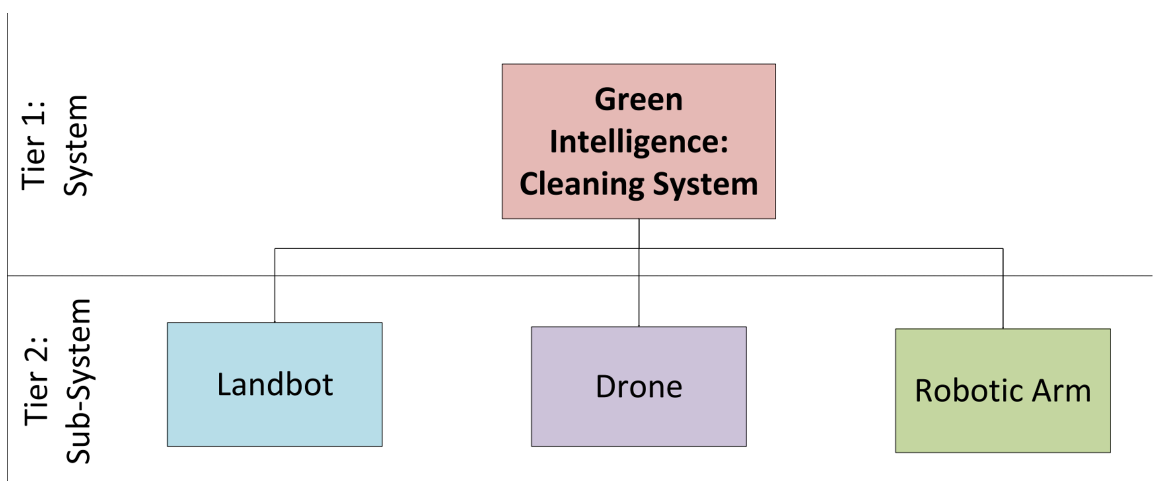

Figure 2. Electrical System Decomposition

Figure 3 presents the hierarchical architecture of the platform, separating high-level AI-driven decision making from low-level autonomous control. The AI-driven layer, implemented on a GPU, performs image-based inference using drone-acquired imagery of solar panels. The autonomous control layer, implemented on a Raspberry Pi and an Arduino Mega, executes deterministic, real-time control of motors and actuators. This separation exposes students to modern cyber–physical system design patterns, illustrating how perception, planning, and actuation are distributed across heterogeneous computing platforms in real robotic systems.

The system architecture integrates electrical, mechanical, and data domains across two cooperating robotic platforms. The drone collects real-time imagery and transmits data to a Raspberry Pi mission controller. Image frames are forwarded to a GPU for AI-based inference, while an Arduino Mega executes low-level motor and actuator commands. Power is supplied by dual 12 V batteries, with regulated 5 V logic conversion and protection through fuses and relays.

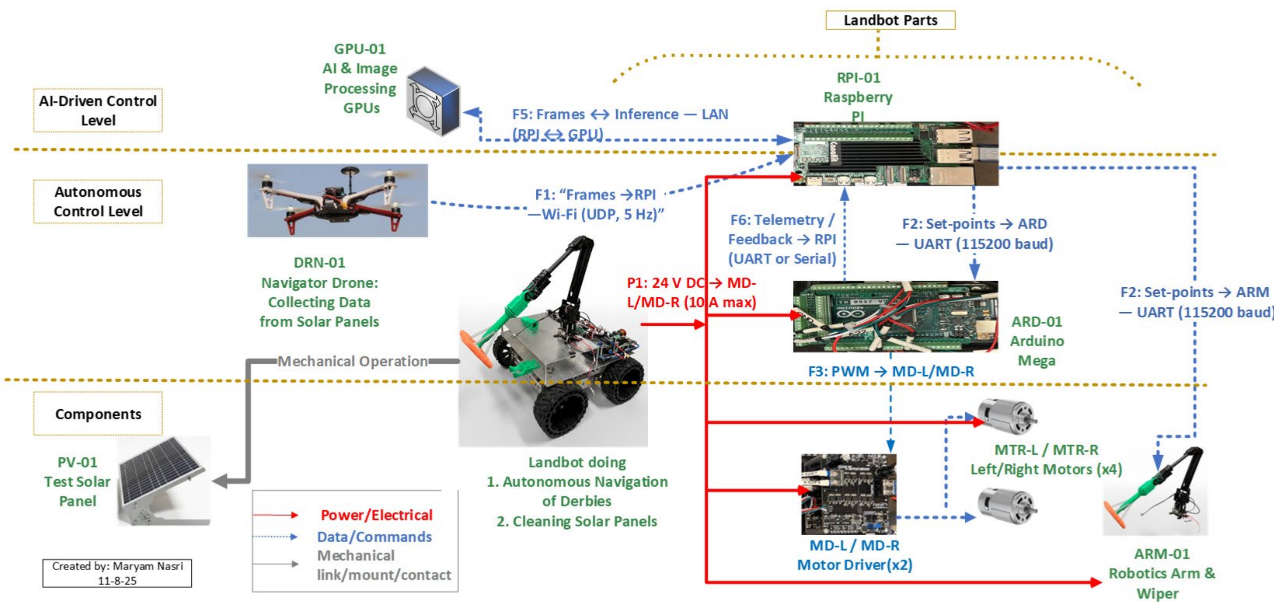

Figure 3. System architecture diagram illustrating the AI-driven layer (GPU-01) and the autonomous control layer (Raspberry Pi, Arduino Mega 2560, and drone). The diagram details data/command interfaces (F1, F2, F5, F6) and power distribution (P1) across the LandBot (ROV-01) and drone (DRN-01) platforms.

Figure 4 illustrates the complete electrical, mechanical, and data interaction loop across the drone, LandBot, and solar panel environment. The diagram emphasizes the tight coupling between sensor data, control signals, and power distribution across subsystems. This visual representation reinforces system-level thinking by demonstrating that robotic performance emerges from the coordinated interaction among power electronics, embedded communication, mechanical actuation, and AI processing, rather than from isolated components.

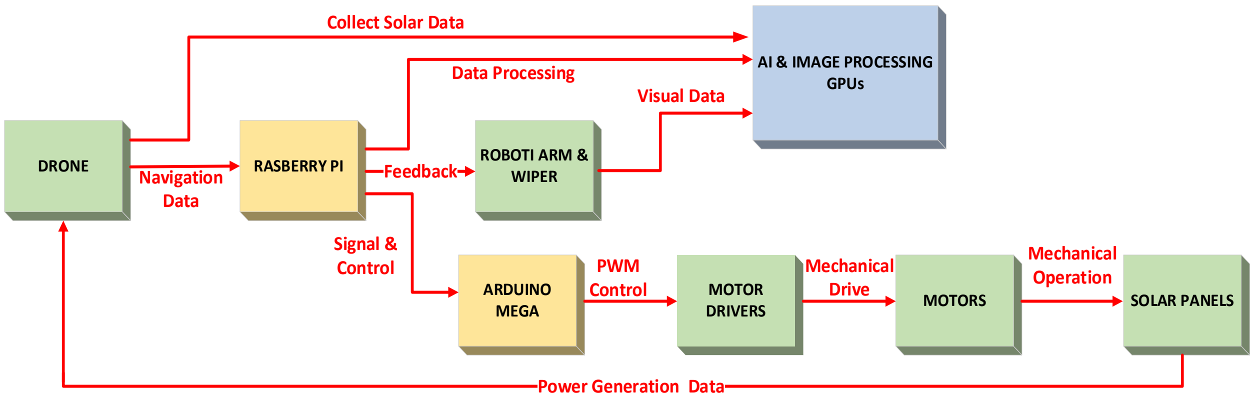

Figure 4. Integrated system workflow illustrating how the drone, Raspberry Pi, Arduino Mega 2560, robotic arm and wiper, motor drives, motors, and solar panel interact through electrical, mechanical, and data pathways. The diagram illustrates data collection, signal processing, feedback, and power transmission across modules for autonomous solar-panel inspection and cleaning.

3. Control Platform for LandBot Subsystem

The Raspberry Pi coordinates perception, decision-making, and actuation. After initial communication is established, the GPU receives and processes live drone imagery. Motion commands are transmitted to the Arduino, and telemetry is logged continuously. Safety monitoring is implemented through emergency-stop and timeout detection functions. The high-level control structure is shown in Figure 5.

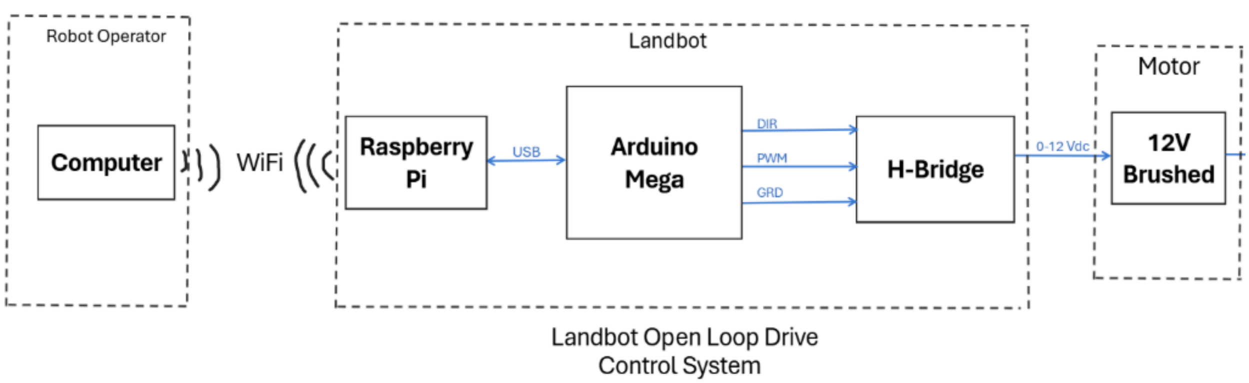

Figure 5. High-level control flow of the Raspberry Pi, which coordinates communication among the drone, Arduino Mega, and GPU. The controller handles image frames, inference results, motion commands, and safety feedback through Wi-Fi and UART interfaces.

4. Prototype Development and Testing

Figure 6 shows the physical realization of the electrical design, emphasizing layout discipline, cable management, labeling, and safety integration. By comparing Figures 5 and 6, students observe the critical transition from schematic abstraction to real-world hardware implementation, an essential professional engineering skill that is often underrepresented in traditional curricula.

The LandBot robot integrates a Raspberry Pi 5, Arduino Mega 2560, dual H-bridges, and 12 V DC motors to ensure reliable power delivery and motion control. The design includes current metering, protective fuses, a 5 V buck converter, and serial UART communication for closed-loop control. Physical implementation emphasizes safety through labeled connections, an emergency stop, and robust cable management.

Bench and field testing verified stable power delivery, responsive control, and robotic arm repeatability, confirming the system's reliability and supporting validation of both the technical architecture and the instructional approach.

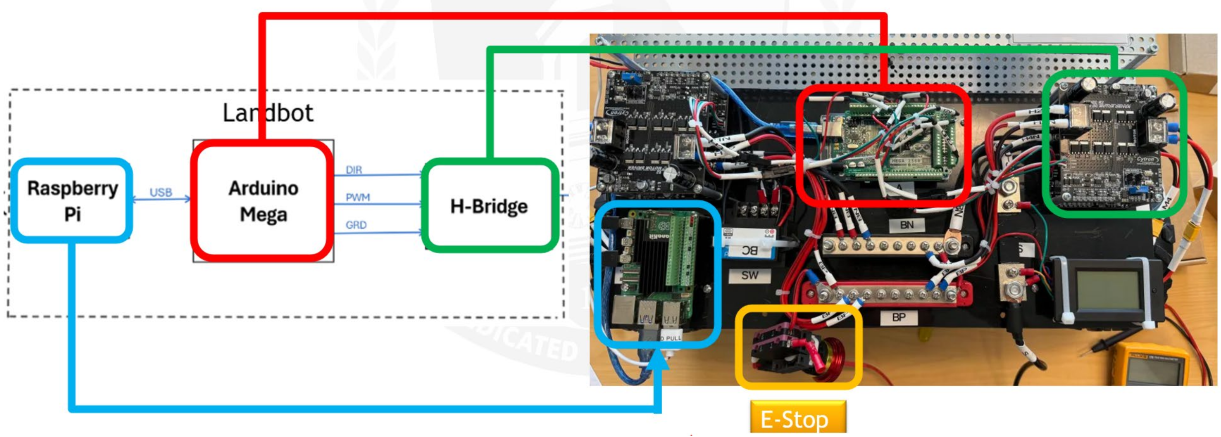

Figure 6. Physical implementation of the electrical and control subsystem showing the Raspberry Pi, Arduino Mega, H-bridges, and safety components.

5. Results

Figure 7 illustrates the electrical control and validation setup of the land-based robotic platform. The left image shows the integrated hardware layout, including embedded controllers, motor drivers, power distribution components, and actuator connections, with four monitored control channels (CH1–CH4) corresponding to coordinated motor and actuator commands. The right image presents oscilloscope traces for these channels, demonstrating synchronized digital control signals and consistent timing behavior across multiple actuators. These measurements confirm reliable embedded communication and deterministic control performance, validating the electrical subsystem design under representative operating conditions.

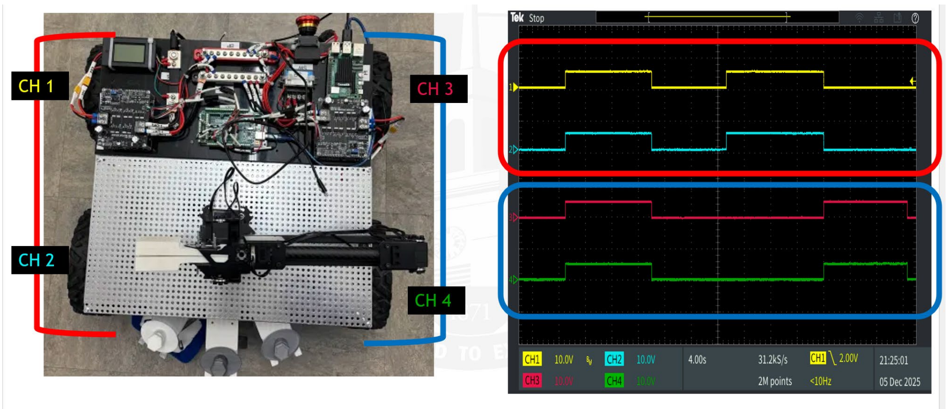

Figure 7. Integrated electrical control hardware (left) and corresponding oscilloscope waveforms (right) showing synchronized multi-channel motor and actuator control signals and validating reliable embedded communication and timing consistency.

6. Evaluation and Assessment Methodology

The Electrical Senior Design I cohort included three project teams: the Robotic Vehicle team, the Resistors team, and the COSMOS team. Each team was evaluated using the same course-embedded senior design rubric. The Robotic Vehicle team included approximately 3 students, while the Resistors and COSMOS teams included approximately 3 and 4 students, respectively. Although all three teams followed a project-based senior design structure, the Robotic Vehicle group differed in the extent of interdisciplinary coordination, hardware/software integration, subsystem coupling, and the level of real-time testing required.

The effectiveness of the AI-driven solar maintenance platform was evaluated using a structured, course-embedded assessment framework implemented in Senior Electrical Design I (ENT 465) and Senior Electrical Design II (ENT 466). Assessment instruments were designed to measure both technical mastery and professional competencies aligned with ABET student outcomes and interdisciplinary learning objectives.

Multiple direct assessment measures were employed, including:

- Design documentation and technical reports
- Oral project presentations and demonstrations
- System integration milestones
- Faculty evaluation rubrics
- Prototype performance validation

These instruments allowed consistent measurement of student performance across system design, implementation, testing, and communication domains.

This multidimensional approach ensures that learning outcomes reflect authentic engineering practice rather than isolated laboratory exercises.

6.1 Assessment Instruments and Performance Metrics

Student learning was evaluated using standardized capstone rubrics embedded within ENT 465/466. These rubrics assess performance across the following core domains:

1. **System Design and Technical Competence**
    - Power distribution and protection design
    - Motor control and embedded communication implementation
    - System-level integration and debugging
2. **Engineering Problem Solving and Experimentation**
    - Validation of current draw, thermal margins, and subsystem reliability
    - Interpretation of telemetry and feedback data
    - Iterative system refinement
3. **Teamwork and Interdisciplinary Collaboration**
    - Coordination with Mechanical Engineering Technology and CIS teams
    - Integration of electrical, mechanical, and AI subsystems
4. **Communication and Professional Practice**
    - Technical reports
    - Oral presentations and system demonstrations

These criteria align directly with the project's interdisciplinary structure and mirror the professional workflow described in the system architecture and prototype development sections.

6.2 Technical Performance Assessment Through System Validation

In addition to rubric-based evaluation, technical performance metrics were embedded into student assessment. Prototype validation tasks were explicitly mapped to course outcomes, including:

- Stable power delivery under variable load
- Reliable wireless command transmission between Raspberry Pi and Arduino
- Repeatable robotic arm positioning
- Safe operation through emergency-stop and fault monitoring

Bench and field testing confirmed that students successfully met these engineering benchmarks, demonstrating mastery of real-world system integration rather than isolated component operation. This coupling of academic assessment with engineering validation is a distinguishing feature of the platform. To improve consistency and rigor in the evaluation, specific technical performance metrics were defined and aligned with course assessment criteria, as summarized in Table 1.

Table 1. Technical Performance Metrics and Corresponding Assessment Measures

Metric	Evidence Collected	Assessment Connection
Power stability	Voltage/current observation during load testing	Electrical design competence
Motor control timing	Oscilloscope CH1–CH4 signals	Embedded control and testing
Wireless command reliability	Successful command transmission trials	System integration
Arm/wiper repeatability	Repeated motion demonstration	Mechanical/electrical integration
Safety response	Emergency stop and timeout behavior	Professional design practice

6.3 Alignment With Capstone Learning Outcomes

The assessment framework explicitly supports ABET-aligned learning outcomes by requiring students to:

- Apply engineering design to complex, multidisciplinary systems
- Conduct experiments and interpret system data
- Function effectively on multidisciplinary teams
- Communicate technical content professionally

Because students progress from funded summer research to two sequential design courses, longitudinal assessment captures growth over an entire year of system development rather than in a single-semester snapshot.

This structure provides stronger evidence of sustained learning gains than traditional standalone projects.

6.4 Educational Effectiveness of the Platform

Assessment results demonstrate that the platform successfully integrates technical rigor with professional skill development. Students are evaluated not only on whether the robot functions, but also on how systematically they design, test, document, and communicate the system.

This directly supports the project's educational goals of:

- Connecting theory to real-world renewable energy systems
- Reinforcing system-level thinking
- Preparing students for multidisciplinary engineering environments

The assessment-driven design of the platform distinguishes it as both a technical research system and a reproducible instructional model.

6.5 Reproducibility and Transferability

Because assessment instruments are embedded into standard capstone workflows, the platform can be adopted by other institutions seeking scalable, outcomes-driven interdisciplinary projects.

The combination of:

- Modular system architecture
- Structured rubrics
- Integrated technical validation

creates a transferable model for project-centered engineering education.

6.6 Comparison Across Project Teams

The comparison among the three teams should be interpreted as course-embedded assessment evidence rather than as a controlled experimental study. Students were not randomly assigned to projects, and the scope, complexity, and technical requirements differed across teams. Therefore, the observed performance differences cannot be attributed solely to the instructional model or to the interdisciplinary structure of the Robotic Vehicle project. Other factors, including student motivation, team composition, prior technical preparation, project complexity, and the level of faculty interaction, may also have contributed to the results. To clarify the context for this comparison, the key differences among the Robotic Vehicle, Resistors, and COSMOS project teams are summarized in Table 2.

As shown in Table 2, the Robotic Vehicle project required a higher level of interdisciplinary integration, hardware–software coordination, and system-level validation than the other teams. These differences provide important context for interpreting the rubric results while avoiding a direct causal claim that the instructional model alone produced the observed differences in rubric-based performance.

Table 2. Comparison of Project Scope, Technical Complexity, and Instructional Features Across Project Teams

Feature	**Robotic Vehicle**	**Resistors**	**COSMOS**
Team size	3	3	4
Project type	Interdisciplinary robotic solar maintenance	Component-level electrical project	Electrical system analysis/design project
Main technical domains	Electrical, mechanical, embedded control, AI	Electrical circuits and analysis	Electrical systems and theoretical modeling
Hardware integration	High	Low	Medium
External collaboration	MET and CIS	None	Limited or none
Validation method	Prototype testing, oscilloscope signals, power/control validation	Circuit testing and analytical validation	Analytical evaluation and limited testing
Assessment rubric	Same senior design rubric	Same	Same

6.7 Cost Analysis and Transferability

While the fully funded project budget was approximately $40,000, a simplified instructional version could be implemented at a lower cost by using a smaller mobile platform, a low-cost camera instead of a drone, and reduced AI/computing requirements. The estimated cost distribution across major system components is summarized in Table 3. These values are based on typical component pricing for the implemented hardware configuration and reflect an approximate range for replicating the platform in an academic setting. With only two months left in the project and grant, $11,500 has been spent on devices, including some to replace damaged arms, a Raspberry Pi, and other small electrical components. The payments to 10 students from Electrical, Mechanical, and Computer Information Systems, as well as to the lab technician and faculty for extra service work, exceeded $12,000. While the full system reflects a higher-cost research implementation, the sensing, mobility, and AI components make the platform more accessible for broader instructional use.

Table 3. Estimated Cost Breakdown for the Solar Maintenance Capstone Platform.

Category	**Approximate Cost**
LandBot/mobile platform (chassis, wheels, frame)	$900–$1,200
Drone (camera + flight system)	$700–$1,200
Raspberry Pi 5 + Arduino Mega + controllers	$250–$450
Motor drivers (H-bridges) and DC motors	$250–$500
Power distribution (batteries, converters, fuses, relays)	$200–$400
Robotic arm and wiper mechanism	$400–$900
Solar panel mock-up and test structure	$200–$500
Wiring, connectors, mounting hardware	$150–$350
Software / AI / GPU support (shared resources)	$800–$1000
GPU/AI Server (NVIDIA)	$4000-5500
Total estimated implementation cost	$7850–$12000

7. Conclusion

During the final Electrical Senior Design I review, faculty members and Industrial Advisory Board representatives evaluated three project teams using the same course rubric. Among these teams, the Robotic Vehicle group demonstrated strong performance across most rubric categories, particularly in system integration, engineering science concepts, and technical presentation.

These results suggest that interdisciplinary, hardware-centered projects can support strong student engagement and technical performance. However, because the comparison was based on course-embedded assessment rather than a controlled study, the results should be interpreted as promising evidence rather than proof of causal superiority.

Figure 8 summarizes the average rubric scores across major assessment categories for the senior project teams. Overall performance indicates strong achievement in engineering science concepts (ESC) and team building, with the Robotic Vehicle group earning the highest scores across most categories. This pattern reflects effective system integration and interdisciplinary coordination. Scores in project management skills and design/documentation were comparatively lower, highlighting areas where additional instructional scaffolding may further strengthen student outcomes.

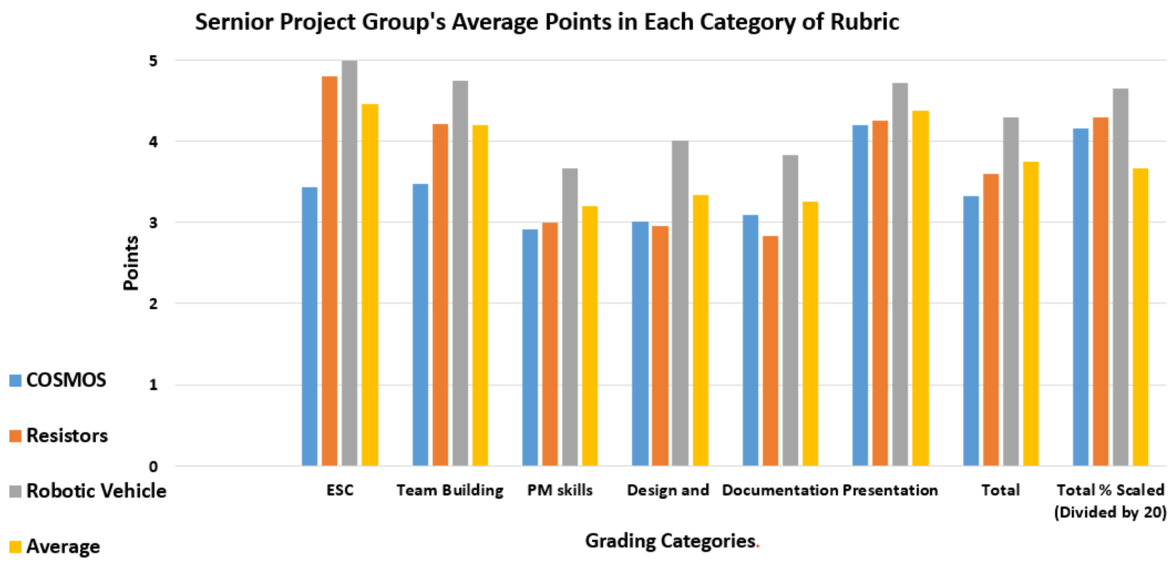

Figure 8. Comparison among three project teams in the Electrical Senior Design I course, with the solar-maintenance project identified as the Robotic Vehicle group.

Presentation scores were uniformly high across teams, suggesting that students effectively communicate technical results. The total and scaled scores demonstrate consistent overall performance among teams, supporting the effectiveness of the project-centered instructional approach while also identifying targeted opportunities for curriculum improvement.

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