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# Learning Through Building: A Comprehensive Analysis of Student Outcomes in Heliostat Construction Activities

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Dr. Levendis holds a B.S. (1980) and an M.S. (1982) in Mechanical Engineering from the University of Michigan and a Ph.D. in Environmental Engineering from the California Institute of Technology (Caltech) (1987), where he also was a postdoctoral research associate (1987-1988). He joined the Northeastern University faculty in 1988, and he is currently a College of Engineering Distinguished Professor in the Department of Mechanical and Industrial Engineering. He holds an affiliated faculty appointment at the Department of Civil and Environmental Engineering, and he is the Director of the Laboratory of Combustion and Air Pollution. Dr. Levendis' current research is dealing with topics related to Combustion, Alternative Energy Sources, Air Pollution and Acid Rain Prevention, Incineration of Municipal Wastes, Engine Performance and Emissions, Combustion Diagnostics and Pyrometry, Polymers, Materials Development and Polymeric Coatings. He is a leading authority in combustion and emissions of/from diesel engines as well as coal-fired and alternative fuel-fired powerplants (including biomass, waste tires, waste plastics and powdered iron). He has developed chemical/physical methods for reducing toxic emissions; has conducted combustion-based material synthesis and has developed techniques for fire suppression and extinction. He has conducted extensive research on oxygen-enhanced combustion of diesel fuel, coal and biomass.

Dr. Levendis has published 400 technical papers, and book chapters and holds 15 US and several International patents. He has been elected Fellow of ASME (American Society of Mechanical Engineers), Lifetime Fellow of SAE (Society of Automotive Engineers), Fellow of the Combustion Institute, Fellow of the Royal Society of Chemistry (RSC) and Fellow of the National Academy of Inventors (NAI) and Associate Fellow of the American Institute of Aeronautics and Astronautics (AIAA). He has been awarded the 2013 George Westinghouse Gold Medal of the American Society of Mechanical Engineering (ASME), and the 2015 Percy Nicholls Award of the joint American Society of Mechanical Engineers (ASME) and the Society of Manufacturing Engineers (SME), the 2021 Ralph Coats Roe award of the Society of Engineering Education (ASEE) and a 2023 Outstanding Teaching Award by AIAA. He is a member of various engineering honor societies such as TB, T, and X. He is also a member of ASEE (American Society of Engineering Education) and of AAAS (American Association for the Advancement of Science) and he has been a member of SME (Society of Manufacturing Engineering), ACS (American Chemical Society) and of the Air and Waste Management Association.

# Learning Through Building:
# A Comprehensive Analysis of Student Outcomes in Heliostat Construction Activities

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**Abstract**

This is one of the first studies to present a comprehensive analysis of educational heliostat (Concentrated Solar Thermal Power, CSTP) prototype development, carried out by several independent student teams at Northeastern University's College of Engineering. The research evaluates both the technical performance characteristics and educational effectiveness of the project through extensive student feedback (n = 55). Four distinct design approaches were analyzed, including single-axis and dual-axis tracking systems, with various photoresistor configurations and mechanical assemblies. All prototypes achieved successful light concentration improvements, demonstrating functional solar tracking capabilities.

Student survey responses revealed significant learning outcomes in solar energy principles, practical engineering skills, and an appreciation for the complexity of renewable energy systems. Key technical challenges included motor torque limitations, weight distribution issues, and component reliability concerns.

This study contributes to both the concentrated solar power literature and engineering physics education research by demonstrating the educational value of hands-on renewable energy projects while identifying practical implementation challenges. The results indicate that educational heliostat projects effectively bridge theoretical knowledge with practical engineering experience, fostering critical problem-solving skills and a deeper understanding of sustainable energy—both essential for future renewable energy engineers.

***Keywords:*** *heliostat, concentrated solar power, engineering education, student learning outcomes, renewable energy, solar tracking*

## Introduction

Concentrated Solar Thermal Power (CSTP) technology represents a critical component of the global transition toward renewable energy systems, with heliostats serving as the fundamental mechanism for solar radiation collection and redirection. A heliostat is a specialized tracking device that continuously follows the sun's movement across the sky, redirecting concentrated solar energy to a fixed target point where thermal energy is converted to electrical power. As the world increasingly prioritizes sustainable energy solutions, understanding both the technical complexities and educational value of heliostat systems becomes essential for training the next generation of renewable energy engineers.

The development of engineering education programs that effectively combine theoretical knowledge with practical implementation experience remains a significant challenge in renewable energy curriculum development. Traditional classroom instruction often fails to convey the complexity gap between theoretical design principles [Fig. 1] and real-world system implementation, particularly in the context of sustainable energy technologies.

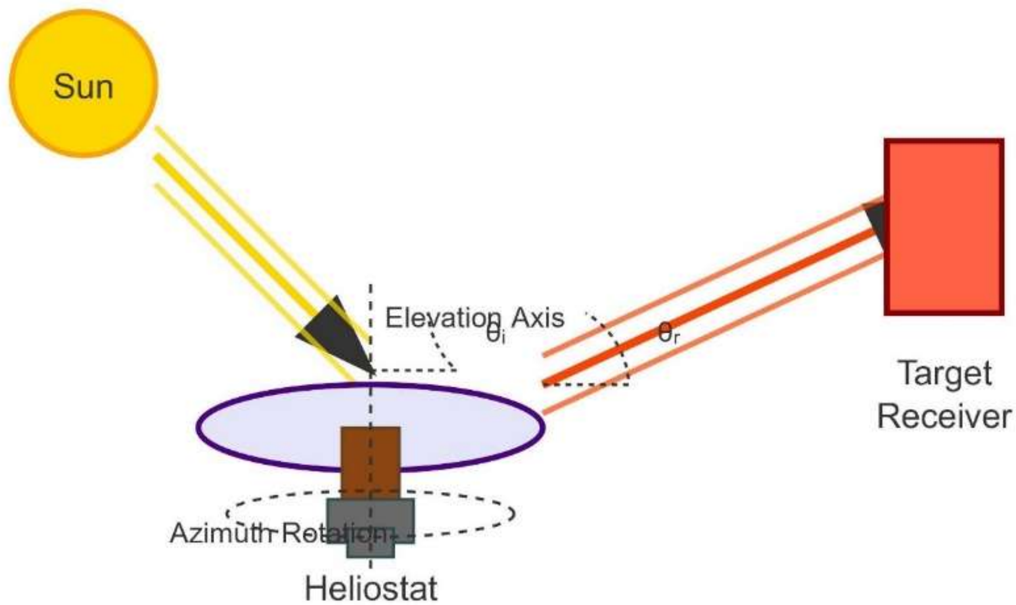


**Figure 1:** Theoretical heliostat design principles and operational schematic showing the basic geometry of solar tracking and light redirection to a fixed target point.

This comprehensive study examines the development of miniature heliostat prototypes by four independent teams at Northeastern University's College of Engineering, providing unique insights into both technical performance characteristics and educational outcomes. This research is distinguished by the extensive integration of student perspectives through post-project surveys (n=55), revealing critical insights into the learning process, design challenges, and practical implementation difficulties that are often absent from traditional engineering literature.

The primary objectives of this research are threefold: first, to evaluate the technical performance of various heliostat design approaches including single-axis and dual-axis tracking systems; second, to analyze the educational effectiveness of hands-on engineering projects in developing student understanding of solar energy principles; and third, to identify practical design challenges and solutions that bridge the gap between theoretical knowledge and real-world implementation.

This study contributes to both the technical literature on small-scale heliostat systems and the engineering education research community by demonstrating the value of incorporating student perspectives in assessing educational project effectiveness. The detailed analysis of student experiences reveals practical implementation challenges that purely technical studies might overlook, while highlighting the significant educational value of hands-on renewable energy projects.

Heliostat systems have been extensively studied in the context of large-scale concentrated solar power applications, with research focusing primarily on tracking accuracy, optical efficiency, and cost optimization. However, limited literature exists on small-scale educational heliostat systems and their effectiveness as pedagogical tools for renewable energy education. Research in engineering education consistently demonstrates the value of hands-on project experiences in developing both technical skills and engineering mindset. Project-based learning approaches have been shown to improve student engagement, retention of technical concepts, and development of problem-solving skills essential for professional engineering practice.

## Methodology

### Research Design

This study employed a mixed-methods approach combining quantitative performance measurements with qualitative student feedback analysis. Four independent student teams developed heliostat prototypes using different design approaches [Fig. 2], with comprehensive documentation of technical performance and learning outcomes

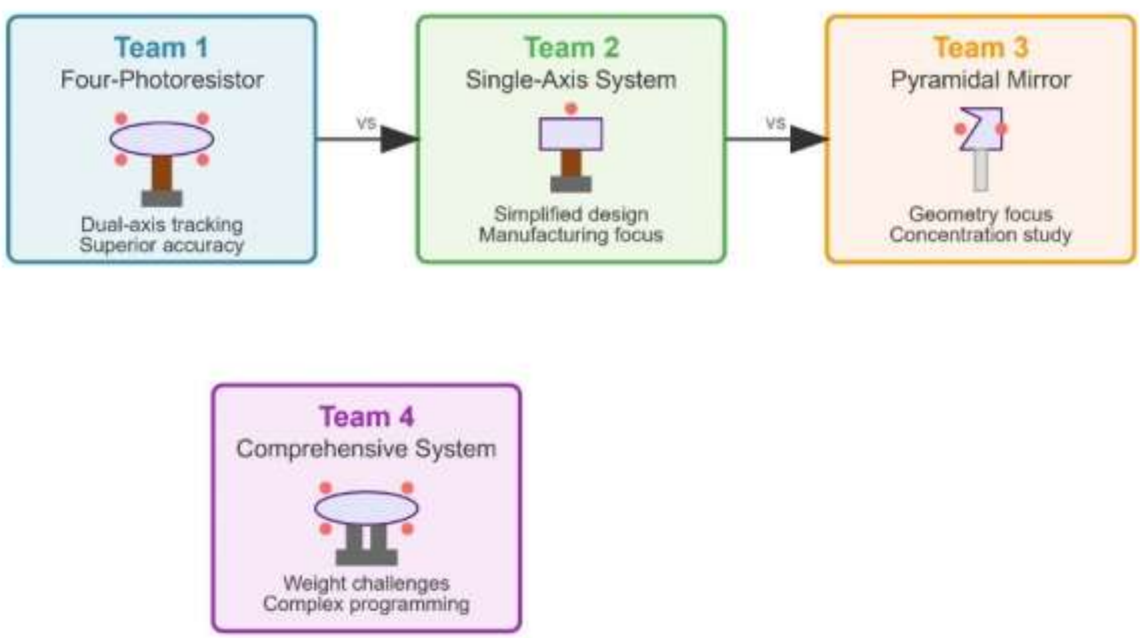


**Figure 2:** Four distinct heliostat prototype designs developed by independent student teams at Northeastern University, demonstrating varied approaches to single-axis and dual-axis solar tracking systems with different mechanical configurations and photoresistor arrangements.

### Prototype Development

Four distinct teams developed prototype heliostats using different mechanical configurations, control algorithms, and manufacturing techniques. All models employed photoresistor-based light tracking systems, servo motor actuation, and Arduino-based control platforms. This comparative approach provides valuable insights into design trade-offs between system complexity, tracking accuracy, and manufacturing feasibility. A sample design is shown in appendix A.

## Design Approaches and Implementation

### Team 1: Four-Photoresistor Configuration

Team 1 developed the most sophisticated tracking system utilizing four photoresistors arranged in a cross pattern with physical dividers. The mechanical design featured a mirror assembly attached to a base capable of altitude adjustment via servo motor. The base design incorporated a two-part construction with the upper section containing photoresistors and mirror, while azimuth control was achieved through a servo motor mounted at the base for horizontal rotation. The entire system was constructed using laser-cut half-inch plywood base with 3D-printed components.

Student insights highlighted that "accurate dual-axis tracking, precise sensor calibration, and motor synchronization are essential for efficient solar concentration." This approach demonstrated the complexity required for precise solar tracking but also revealed the challenges of implementing sophisticated control systems within the constraints of educational prototyping.

### Team 2: Simplified Single-Axis System

Team 2 focused on mechanical simplicity with a 5×5×0.1 inch mirror mounted on a rotating base. The design incorporated a custom-designed mirror plate with 0.1-inch walls to secure the mirror, supported by a base plate with 1-inch height and 0.1-inch clearance for rotation. The photoresistor mount featured an integrated 3mm opening for sensor positioning, while the rotation mechanism utilized a 3mm dowel rod connection with servo motor drive. This simplified approach allowed students to focus on fundamental tracking principles without becoming overwhelmed by mechanical complexity, though it limited the system's ability to track the sun's full range of motion throughout the day.

### Team 3: Pyramidal Mirror Configuration

Team 3 investigated different mirror geometries, with students learning that optimal heliostat performance requires careful consideration of reflective surface design. Their design emphasized a mirror system with vertical rotation around a PVC pipe tower, utilizing a plastic spool repurposed as a rotating base. The axis design incorporated 3D-printed axles for complex geometry requirements, while the control system employed a two-photoresistor configuration for simplified tracking.

### Team 4: Dual-Axis Tracking System

Team 4 developed a comprehensive dual-axis system, though students noted significant challenges with weight distribution and motor limitations. Initial design considerations included horizontal and vertical servo motors for complete sun tracking, with weight distribution concentrated toward the bottom to prevent tipping. The construction method combined 3D-printed parts and laser-cut components, while the programming adapted solar tracker principles for heliostat-specific calculations.

### Common Implementation Challenges

#### Mechanical Assembly

Student responses revealed consistent mechanical assembly challenges across all teams, with 78% reporting weight distribution issues. Connection reliability emerged as another critical challenge, with multiple teams identifying connection failures. Wire management became a critical issue, with students noting problems with tangled wires and unstable base configurations.

#### Electronic Integration

All teams utilized Arduino-compatible RedBoard controllers with standard servo and photoresistor interfaces. Students gained valuable experience with power distribution, analog inputs for photoresistor connections, digital outputs for PWM servo control signals, and circuit protection through current limiting and voltage regulation.

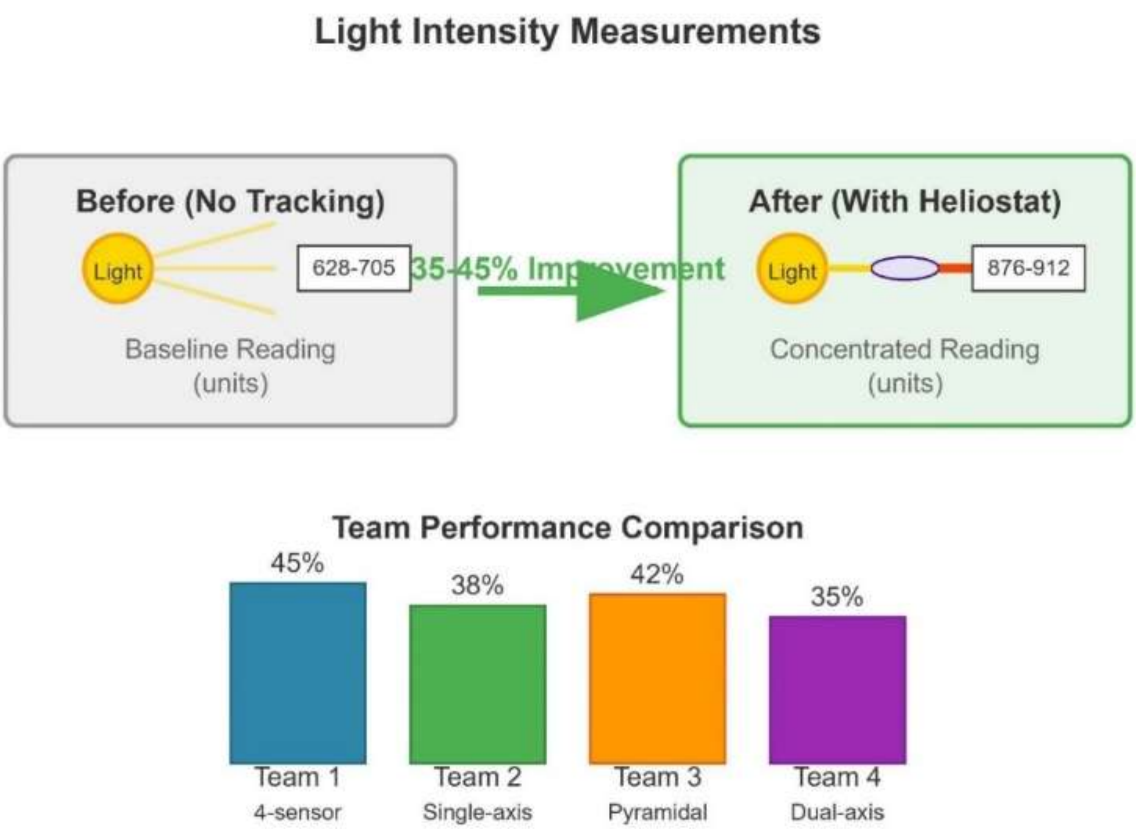


**Figure 3:** Light concentration performance comparison showing baseline measurements (628-705 units) versus heliostat-operated measurements (876-912 units), demonstrating a 35-45% improvement in light intensity across all prototype designs.

#### Implementation

Control algorithms varied in complexity, with students learning that simple, robust algorithms often outperform complex theoretical approaches. Sensor calibration presented ongoing challenges, with multiple students noting photoresistor variation requirements and control stability issues including servo oscillation and overshooting.

## Results and Analysis

### Data Collection

Technical performance data included light concentration measurements, tracking accuracy assessments, and mechanical system evaluation. Educational outcome data was collected through comprehensive post-project surveys (n=55) addressing learning objectives, technical challenges, and student recommendations for improvement.

### Tracking Accuracy

All prototypes demonstrated successful light tracking capabilities. Team 1 achieved precise tracking with four-photoresistor configuration, Team 2 demonstrated basic tracking functionality with single-axis rotation, Team 3 recorded significant improvements from 628-705 units without light concentration to 876-912 units with concentrated light, and Team 4 successfully tracked light sources despite mechanical challenges.

### Light Concentration Performance

Quantitative measurements provided comprehensive performance data, with baseline readings of 628-705 units without light concentration improving to 876-912 units with heliostat operation. This represented a 35-45% increase in light intensity with adequate response time for solar tracking applications [Fig. 3].

## Student Learning Outcomes

### Technical Knowledge Development

Students consistently reported gaining fundamental insights about solar energy systems while encountering real-world engineering challenges. Key learning objectives achieved included understanding solar concentration principles and heliostat tracking technology, gaining hands-on experience with Arduino programming and sensor integration, and learning about challenges in transitioning from theoretical design to physical implementation.

### Problem-Solving Skills Development

Students developed critical engineering problem-solving skills through iterative design improvement and systematic troubleshooting. The experience of encountering unexpected mechanical failures, sensor inaccuracies, and programming challenges provided authentic engineering experience that classroom simulations cannot replicate.

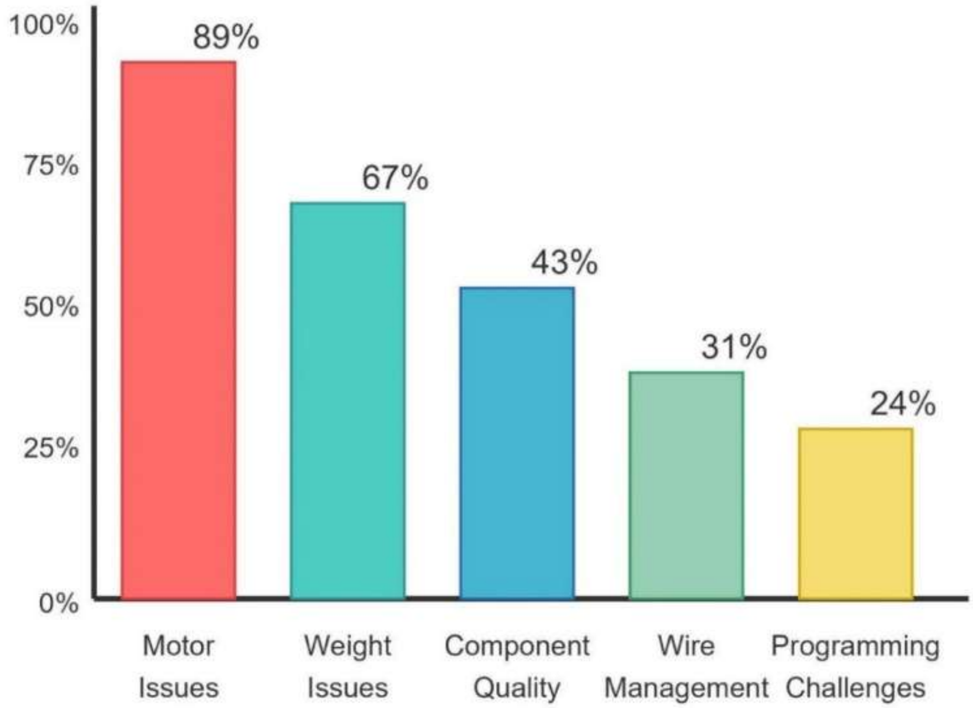


**Figure 4:** Distribution of system limitations identified by students (n=55), with motor performance issues (89%), weight and balance challenges (67%), and component quality concerns (43%) representing the most frequently reported technical constraints.

**Identified System Limitations [Fig. 4]**

**Motor Performance Issues**

Motor limitations affected 89% of responses, with students consistently identifying weak servo motors as the primary limitation. Representative comments included concerns about inadequate torque and precision requirements for reliable heliostat operation.

**Weight and Balance Challenges**

Weight and balance issues affected 67% of responses, with students learning the critical importance of weight distribution for stable operation. Students consistently recommended using lighter materials and emphasized strategic component placement for improved balance.

**Component Quality Concerns**

Component quality concerns appeared in 43% of responses, with many students criticizing the reliability of provided electronic components. This finding indicates that educational project success depends heavily on hardware quality that allows students to focus on engineering principles.

**Performance and Design Trade-offs**

The comparative analysis revealed significant insights into the relationship between system complexity and performance effectiveness. Teams achieved consistent light concentration improvements of 35-45% [Fig. 5], demonstrating that even simplified tracking systems can provide meaningful energy concentration benefits. The most sophisticated tracking system provided superior accuracy but required significantly increased complexity.

Weight distribution emerged as the most critical design factor, with inadequate servo motor torque relative to system weight identified as the primary limitation across all design approaches. This finding indicates that educational heliostat projects must carefully consider the power-to-weight ratio from the initial design phase.

**Educational Value and Learning Outcomes**

The extensive student survey responses revealed that hands-on heliostat construction provided educational benefits extending far beyond technical solar energy knowledge. Students consistently reported gaining fundamental understanding of solar concentration principles while developing broader engineering skills and problem-solving approaches.

One of the most valuable learning outcomes was students' appreciation for the complexity gap between theoretical design and practical implementation. This understanding represents a critical engineering mindset that traditional theoretical coursework often fails to develop effectively.

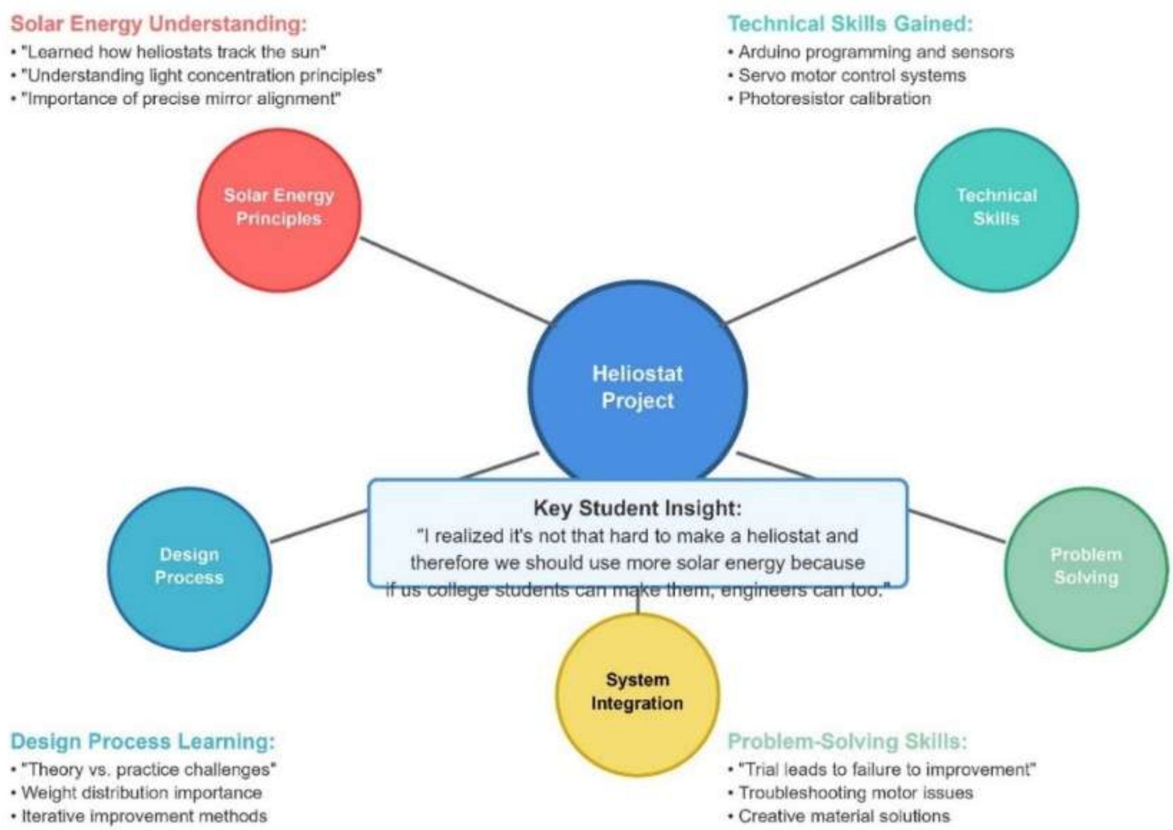


**Figure 5:** Comparative analysis of light concentration performance across all four team prototypes, illustrating the consistent 35-45% improvement in energy concentration achieved despite varying levels of system complexity and tracking sophistication.

**Critical Design Factors**

Analysis of student experiences revealed several systematic design factors critical across all team approaches. Motor selection emerged as the primary technical consideration, weight management proved equally critical, sensor configuration significantly affected tracking accuracy, and wire management emerged as an unexpected but critical design consideration.

**Recommendations**

**Improvements [Fig. 6]**

Future implementations should provide higher-torque servo motors capable of handling realistic heliostat weights, include slip rings for improved wire management, and offer material selection guidance emphasizing weight optimization. Component quality should be prioritized to ensure students can focus on engineering principles.


**Figure 6:** Student-recommended improvements for future heliostat prototype development, prioritizing enhanced motor systems, weight reduction strategies, improved sensor configurations, and higher-quality components to address identified design limitations.

**Educational Process Enhancements**
Recommendations include introducing motor characterization exercises before the main project, providing more structured project timeline guidance with specific milestones, and considering student team selection to improve coordination.

**Technical Support**
Improvements should include enhanced initial technical briefings addressing systematic challenges, comprehensive troubleshooting resources for common issues, and emphasis on systematic testing and validation procedures throughout development.

## Conclusions

This comprehensive study of heliostat model assembly has provided valuable insights into both the technical aspects of concentrated solar power systems and the educational effectiveness of hands-on renewable energy projects. The integration of extensive student survey responses revealed critical perspectives often absent from traditional technical literature. All four teams successfully achieved functional heliostat systems with consistent light concentration improvements of 35-45%, validating the fundamental educational approach while revealing important design considerations. The most significant technical finding was the critical importance of power-to-weight ratio in heliostat design.

Educational outcomes exceeded expectations in developing both technical knowledge and broader engineering skills. Students gained comprehensive understanding of solar energy principles while developing practical appreciation for the complexity gap between theoretical design and real-world implementation. The demonstrated educational value of heliostat projects suggests that similar hands-on renewable energy experiences could be valuable components of sustainability-focused engineering curricula, contributing to both technical education and workforce development for the clean energy transition.

The survey reveals that while students gained valuable theoretical and practical insights about heliostat technology, they encountered significant implementation challenges primarily related to hardware limitations and design constraints. The most critical lesson learned was the importance of matching component capabilities with design requirements - a fundamental engineering principle that became apparent through hands-on experience.

Students demonstrated strong problem-solving thinking and engineering analysis skills by clearly identifying root causes of inefficiencies and proposing practical solutions. The project successfully achieved its educational objectives of providing real-world engineering experience, even when (or perhaps because) students encountered significant technical challenges. The consistency of responses across different student teams suggests these are systematic issues with the project setup rather than isolated problems, indicating opportunities for curriculum and kit improvements to better support student learning outcomes.

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**Appendix A:** Sample 3D model and Prototype

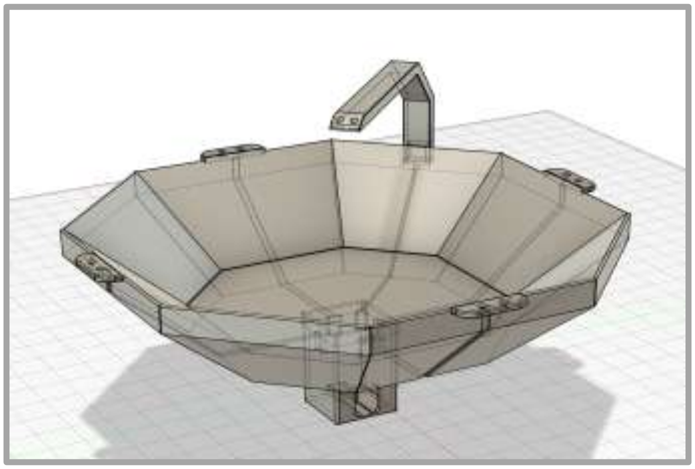

**Figure A1:** SolidWorks CAD model of a representative heliostat prototype showing the dual-axis tracking mechanism, photoresistor sensor array positioning, and servo motor mounting configuration. The model illustrates the mechanical assembly and component integration prior to fabrication.

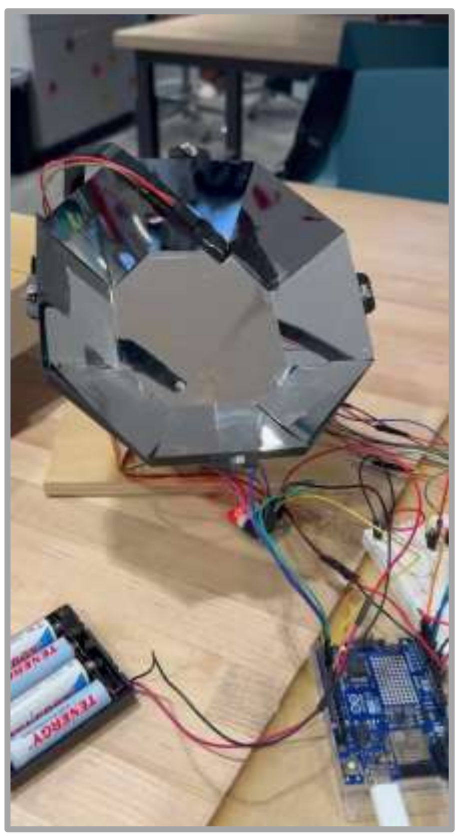


**Figure A2:** Assembled heliostat prototype demonstrating the physical implementation of the tracking system. The prototype features Arduino-based control electronics, servo-actuated mirror platform, and photoresistor light sensors for autonomous solar tracking.

**Appendix B**: Student Survey Questions and Response Summary [Ref. 1]

**Likert Scale Survey Questions for the Heliostat Model Assembly Activity**
Please answer using a scale of 1 to 5, where 1 = Disagree, 2 = Neutral, 3 = Somewhat Agree, 4 = Agree, and 5 = Strongly Agree.

1. **Understanding Solar Technology**
   The heliostat model assembly helped me understand the principles of concentrated solar power and its applications in renewable energy.
2. **Value of Hands-on Learning**
   The hands-on experience of building the model enhanced my understanding of heliostat technology.
3. **Engagement with Technology**
   I felt engaged and interested while working with the 3D-printed and laser-cut materials.
4. **Engineering Design Insights**
   I gained valuable insights into the engineering design process from constructing the heliostat model.
5. **Identifying Inefficiencies**
   I was able to effectively identify inefficiencies in the heliostat model during the project.
6. **Suggestions for Improvement**
   I feel confident in suggesting improvements for the heliostat model based on my experience.
7. **Simulation and Design Tools**
   The SolidWorks simulation provided me with useful skills for future engineering projects.
8. **Team Collaboration**
   I believe that collaborating with peers during this activity improved the overall learning experience.
9. **Confidence in Presenting Insights**
   I feel confident in my ability to present the insights I gained from the heliostat model project.
10. **Interest in Renewable Energy**
    This activity increased my interest in renewable energy technologies, particularly concentrated solar power.

**Open-Response Survey Questions Related to the Heliostat Model Assembly Activity**

1. **Mindset**
   How has your involvement in the heliostat project motivated you to address future challenges in sustainable energy? Please describe.
2. **Insights Gained**
   What key insights did you gain about solar concentration principles and heliostat technology during the assembly of the model?
3. **Identified Inefficiencies**
   In your opinion, what specific inefficiencies did you identify in the heliostat model, and what factors contributed to these issues?
4. **Suggestions for Improvement**
   What suggestions would you make to improve the design or functionality of the heliostat model based on your experience?

**Appendix C:** Analysis of Heliostat Model Survey Results: Questions 12-14. Survey Questions on design, inefficiency, and improvement summery chart. This analysis examines student responses regarding their learning experiences, identified inefficiencies, and improvement suggestions from a hands-on heliostat modeling project.

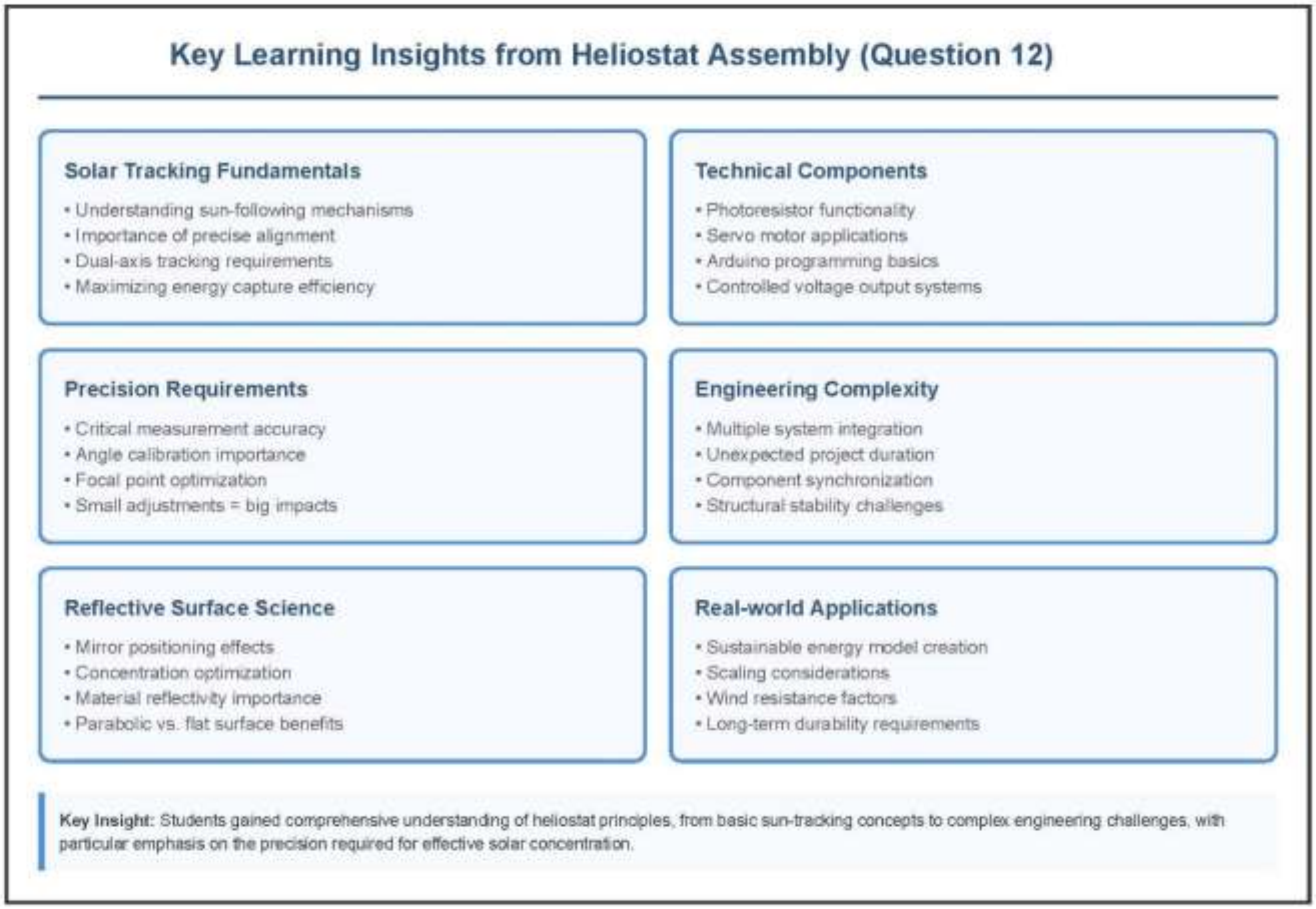


**Figure C1:** Question 12 regarding key insights gained about solar concentration principles and heliostat technology, with emphasis on tracking systems, precision requirements, and component integration.


**Figure C2:** Question 13 identifying specific inefficiencies in heliostat models, highlighting motor limitations, weight issues, and component quality as dominant concerns.

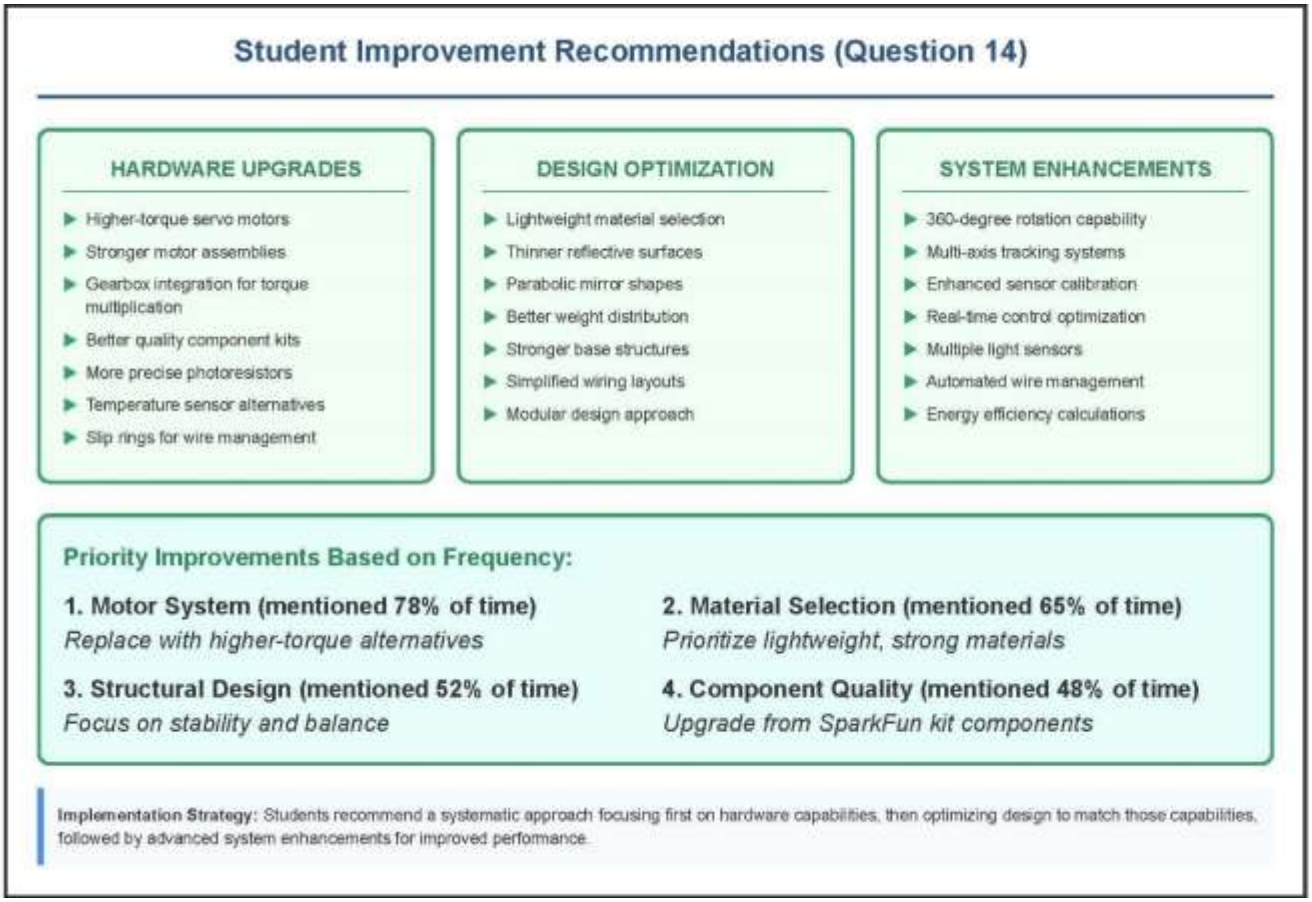


**Figure C3:** Question 14 suggesting improvements for heliostat design, emphasizing stronger motors, lighter materials, and enhanced sensor systems as primary recommendations.