Engineering Sustainable Solutions: The Plant Wall Project as an Interdisciplinary Approach to Integrating Design, Botanical Science, and Educational Innovation

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Introduction

The Plant Wall project is an ongoing senior design initiative aimed at the intersection of advanced engineering and environmental biology to foster innovative solutions for sustainable plant growth systems [11]. The project seeks to create a highly efficient and scalable plant support and irrigation infrastructure that incorporates mechanical and biological considerations for optimal plant development. This interdisciplinary collaboration between the Engineering and Biology Departments enables the application of diverse expertise to address complex challenges related to environmental management and plant growth technologies. The project provided the plant lab students with a hands-on experience, moving beyond textbooks to tackle real-world challenges, from plant selection to pest management.

The mechanical design, a key milestone achieved during the project's first phase, involves creating a structure that can support various plants while offering sufficient space and optimal conditions for growth. This stage focused on ensuring that the design could accommodate the physical needs of different plant species, including factors such as structural stability, space allocation, and environmental exposure. By utilizing advanced engineering principles, the Plant Wall system is designed to promote an eco-friendly and sustainable growing environment within limited spatial constraints.

Urbanization has led to significant reductions in green spaces, adversely affecting biodiversity and sustainability. Vertical gardening offers a way to maximize greenery in limited spaces, but traditional systems often lack adaptability and resource efficiency. The Plant wall Project overcomes these limitations by incorporating smart technologies into a modular, scalable design. The system is tailored to improve plant health, reduce water waste, and minimize maintenance, aligning with sustainability goals for urban agriculture and environmental conservation.

The current phase of the project is to develop an intelligent irrigation system that integrates innovative technologies, such as sensors, automated controls, and data-driven algorithms. This system monitors vital environmental variables, including moisture levels, temperature, and nutrient concentrations [1]. By allowing precise control over these parameters, the innovative irrigation system aims to create an optimized plant growth environment, promoting water conservation and healthy plant development. The ability to remotely control and adjust these variables in real-time adds the technological sophistication essential for modern, sustainable teaching.

Collaboration with the Biology Department has been instrumental in identifying and addressing the unique biological needs of plants within this system. For the biology team, participation was voluntary, and their learning process was guided by feedback and collaborative effort with engineering students. By combining engineering design with biological research, the Plant Wall project addresses complex interdisciplinary challenges such as nutrient delivery, light optimization, and growth cycle management. This cross-departmental effort ensures that the system is not only technically sound but also tailored to the specific growth needs of plants.

Over the academic year, biology and engineering students met weekly to collaboratively shape the plant wall project. Their discussions ranged from identifying plant requirements and debating suitable substrates to devising strategies for climbing plants and selecting the right net pot sizes. Students also tested prototypes, refined watering methods, and evaluated plant vitality across light and placement conditions. These weekly interdisciplinary meetings created an inquiry-based learning environment that mimicked real-world problem-solving and allowed students to gain practical experience by iterating on design decisions collaboratively.

The project's primary objectives are to develop an innovative, technologically advanced irrigation system and to provide students with practical, hands-on experience in applying engineering principles to real-world environmental challenges [2]. By integrating the latest advancements in technology, the project aims to contribute to sustainable development in engineering and plant growth management while fostering an enhanced educational experience. Beyond technical objectives, this project aimed to provide a rich educational experience. For engineering students, it offered opportunities to apply theory to an integrated system combining CAD modeling, prototyping, and environmental control. Biology students engaged in applied plant science, pest control, and light optimization. The hands-on nature of the work fostered soft skills such as collaboration, adaptability, and creative problem-solving. This project aligns with constructivist and experiential learning theories, as students learned through doing, reflection, and peer feedback.

Applicable Standards

The project adheres to the NSPE Code of Ethics, emphasizing safety, health, and welfare of the public. To address expertise gaps in botany, consultations were sought from vertical farming businesses and the Biology Department. The biology team's involvement was voluntary and not formally assessed, but their contributions were integral to the project's development. The team also followed IEEE standards for environmental monitoring and OSHA regulations for safety. ASHRAE Standard 62.1 was consulted for indoor air quality and ventilation, while ASTM D2488-17 guided soil classification. These standards ensure that the project meets safety, environmental, and plant growth requirements, guaranteeing a sustainable and effective design [4, 5].

Manufacturing Strategy

The selection of materials for the design was based on key factors such as weight, tensile strength, and ease of manufacturability. For the supporting frame of each module, we utilized 80/20 aluminum extrusions, a prefabricated material widely used for modular construction. This material is manufactured in bulk and offers a range of components that facilitate easy assembly and customization. The frame's versatility allows for easy adaptation to the required shape and dimensions.

In addition, the team opted to incorporate 3D printing for creating smaller, customizable components. Given the project's scale – falling between hobby-level and full-scale manufacturing – the biology department provided the team with three Elegoo Neptune 4 3D printers. The decision to use the Neptune 4 model was based on its fast print speed and larger print size, which are advantageous for producing the components required for the project. These printers will remain available to the biology department for future research and collaborative projects.

Design Iteration

The project began with an initial drawing, as shown in Figure 1, which provided a conceptual framework for the design.

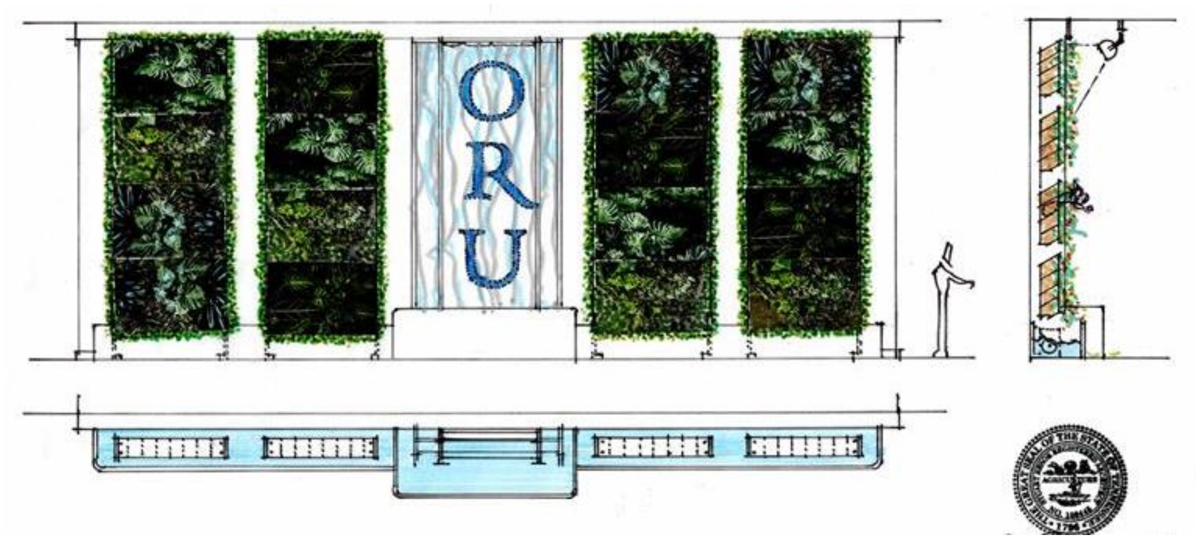

Figure 1: Initial drawing of the design.

Subsequently, we translated this drawing into a precise SolidWorks model, incorporating exact dimensions.

The next phase involved the creation of a physical prototype. Figure 2 shows the constructed prototype.

Figure 2: Completed prototype with front and back views.

After further analysis, the team decided to modify the design to improve efficiency. The middle aluminum support was removed to reduce material usage, but this required the rods to be better supported. In response, new 3D-printed brackets were designed to reinforce the rods, and the rod diameter was increased for enhanced strength.

3D Printed Part Design

To facilitate the attachment of plant pots to the horizontal rods, we designed 3D-printed adapter brackets labeled "pot holders." These brackets feature clips that require minimal force to attach and detach from the rods. Fatigue testing of the clips and Ansys structural simulations were conducted to ensure the stability and durability of the design. The pot holders are designed to securely fit 6-inch plant pots, though the design can be modified for different pot sizes.

Figure 3: 3D-printed pot holder.

We also designed brackets to support the horizontal rods within the module. The bracket design utilizes triangular trusses to distribute the load evenly across the module's back plate. Initially, a cantilevered beam system was used to support the rods, but after analysis, we found that the center support beam was ineffective. The updated design incorporated an additional support beam to better manage the weight distribution, and slotted mounting holes were added to allow for adjustable positioning when attaching to the back wall.

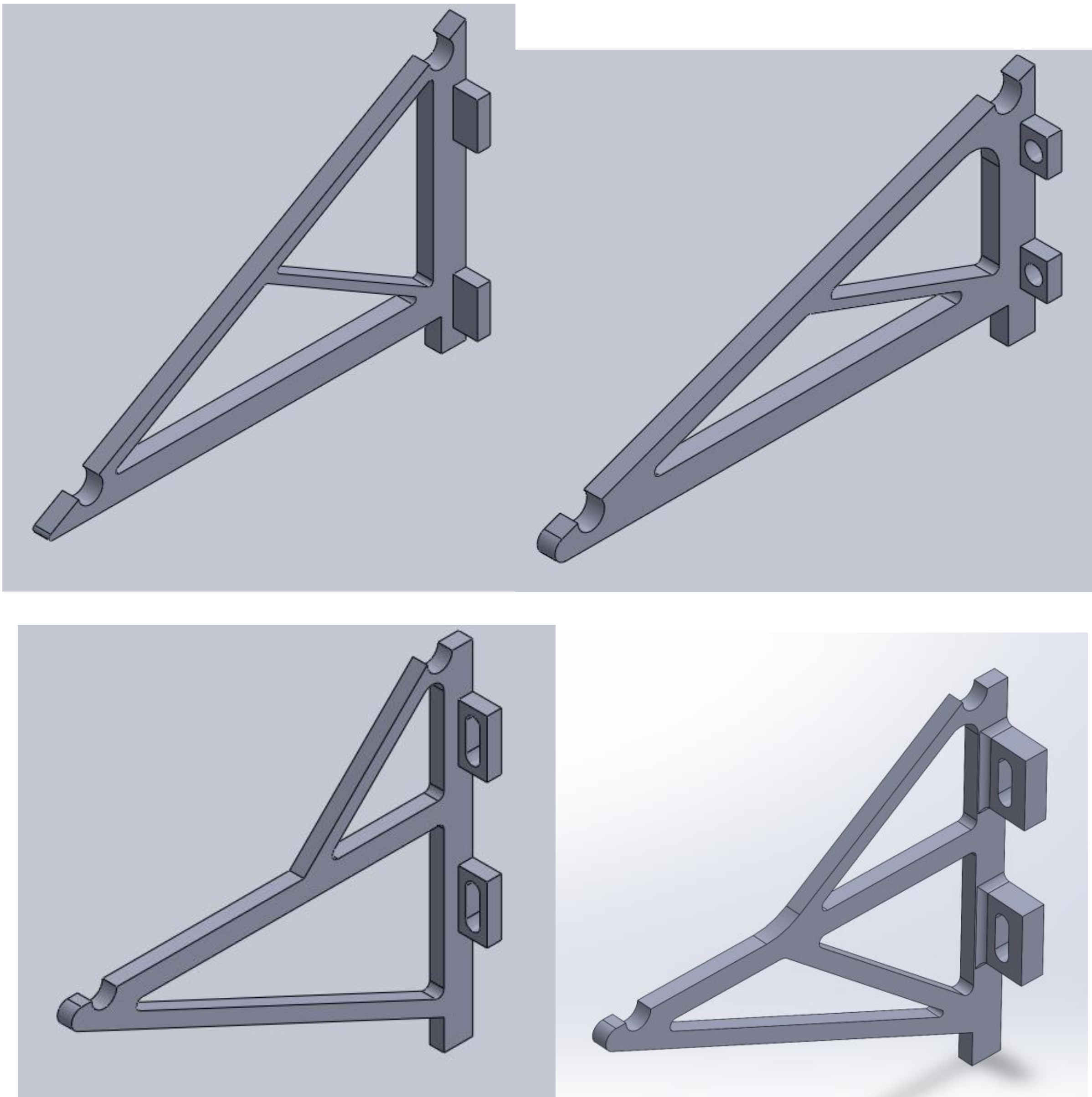

Figure 4: Bracket designs, V1-V4.

After several iterations, the final bracket design was more geometrically complex but significantly stronger due to the improved truss structure and a larger interface footprint.

Irrigation

Irrigation plays a central role in the success of vertical plant walls. As highlighted in the Journal of Applied Science, Engineering, Technology, and Education, efficient irrigation systems are crucial for the design of vertical plant systems. A mist irrigation kit was used for the prototype, including adjustable nozzles and modifiable tubing to meet the system's flow requirements. The tubing is connected to brass fittings that transition from larger diameter tubing to smaller irrigation tubing, which is then connected to the submersible pump, recirculates the water within the irrigation system. The pump was chosen for its low maintenance needs, quiet operation, and cost-effectiveness, all of which are essential for its placement near a seating area and professors' offices. It is powerful enough to push water through the small diameter tubing to the nozzles at the top of the plant wall while keeping noise levels to a minimum.

Experimental Measurements and Testing

Force Gauge Testing for 3D-Printed Pot Holder Clip

The design of the 3D-printed pot holder incorporated a feature allowing it to hook onto a rod that runs through the entire module. To assess the force required to remove the pot holder from the rod, a force gauge was employed. The testing procedure involved using tape and a hook attached to the force gauge.

It is essential to account for human error in such experiments. Variations in the angles at which force was applied, the positioning of the second person's hands holding the rods, and the speed of force application could all influence the test results. These factors contributed to a standard deviation of 2.57, which exceeds the acceptable range for this type of data. Outliers, identified as attempts 6 and 7 with forces of 21.4 and 20.5 Newtons, were excluded from the results. These values were significantly lower than the average force of 27.972N. Figure 5 illustrates the distribution of the data, which aligns with the observed standard deviation. The graph indicates a downward trend in the force required to remove the pot holders over time, suggesting a reduction in the force needed due to the plastic's deformation. This trend is critical in evaluating the cycle life of the pot holders, as it predicts when failure might occur under ideal conditions.

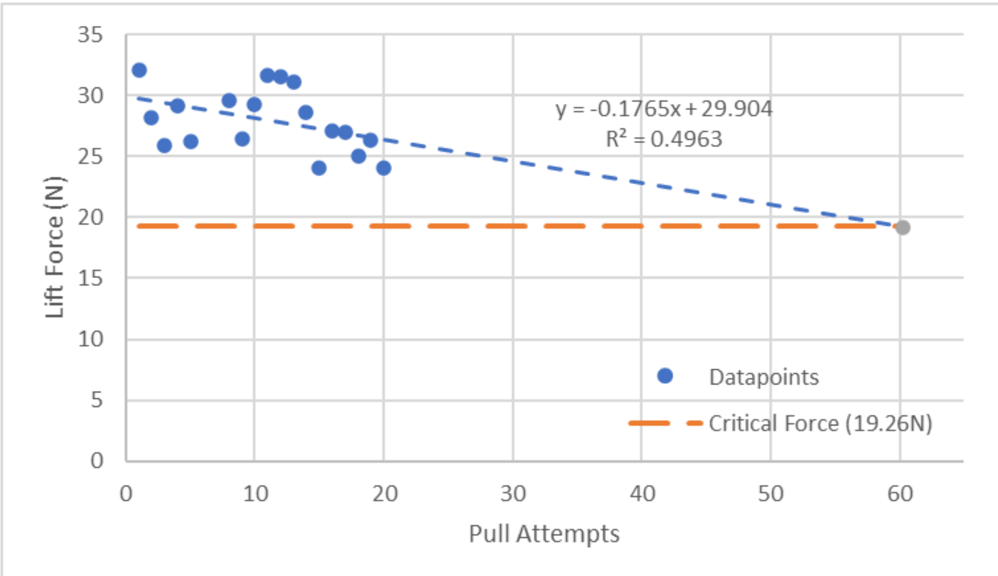

Figure 5: Force vs. Attempts graph.

Figure 6 provides a free-body diagram of the pot holder, depicting the external forces acting upon the holder, such as the applied force pulling the holder upward off the rods. The diagram includes the normal force due to the holder's mass, gravitational force acting on the center of mass, and the resistance from the clips that prevent the pot holder from being removed. The "impending force" refers to the force required to detach the holder and is not constant, occurring only during operator action. The angle of the pot holder is assumed to be 30 degrees relative to the vertical.

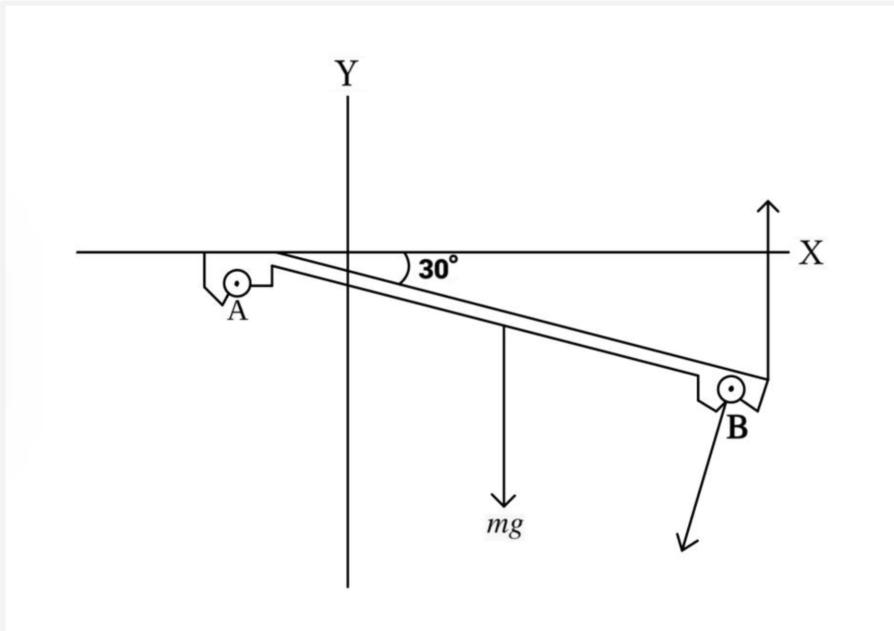

Figure 6: Free Body Diagram for Impending Force.

The manufacturer of the PLA plastic used in the pot holders estimates a lifespan of 12 to 18 years. However, considering various influencing factors such as exposure to water, potential human error, and overuse, our calculations suggest that the PLA material will fail after approximately 7.54 years of operation before experiencing inoperable damage, as detailed in the appendix.

ANSYS Testing for 3D-Printed Pot Holder

Several design constraints were identified for the pot holder, including its weight-bearing capacity. Based on recommendations from the biology department, we estimated that a fully saturated plant (including the pot, substrate, and plant matter) would weigh up to 7 pounds. Consequently, the 3D-printed brackets must support this weight, with each row of steel rods needing to support 70 pounds and each module supporting up to 280 pounds. To ensure a reasonable safety factor, the design accounted for 10 pounds per plant and 400 pounds per module.

Figure 7 show the results of Ansys simulations for total deformation and safety factors, respectively. These simulations confirm that the 3D-printed pot holder is strong enough to support the estimated weight.

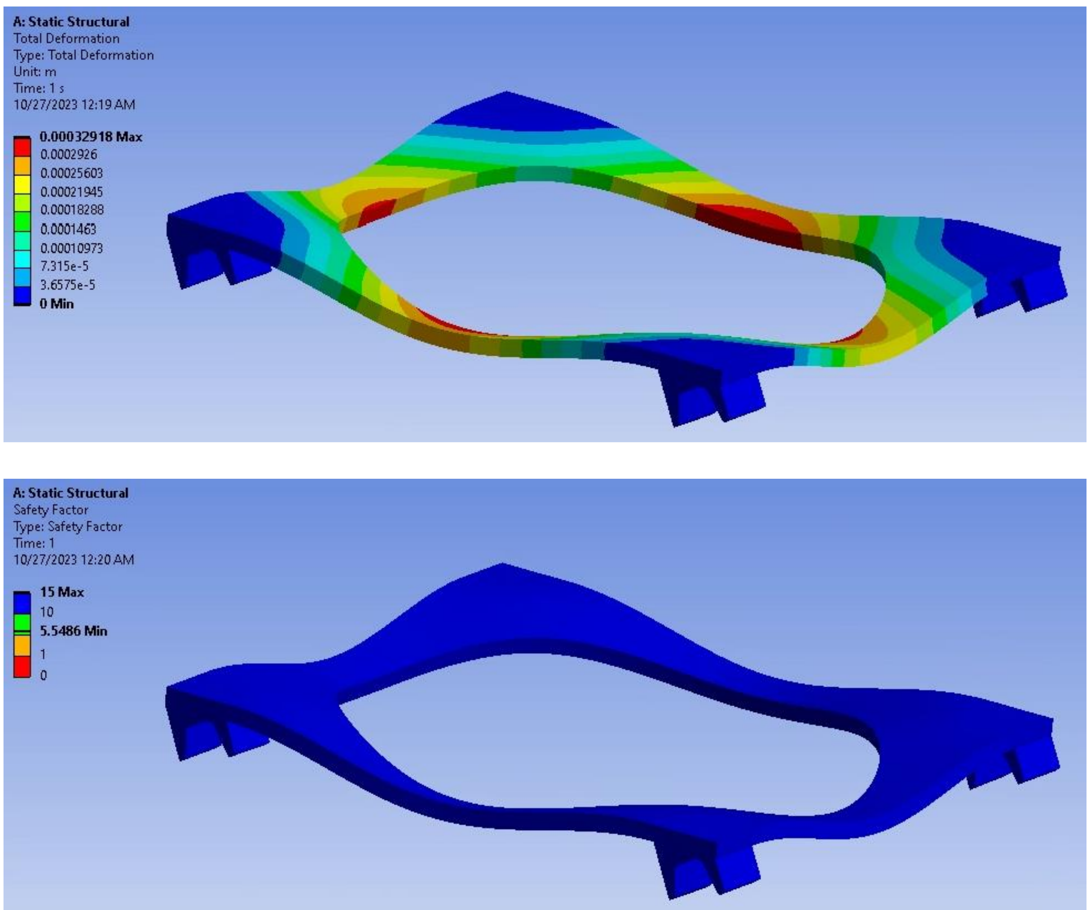

Figure 7: Ansys Simulation of Total Deformation and Safety Factor.

3D-Printed Bracket ANSYS Testing

Further Ansys simulations were conducted for the brackets designed to support the rods. Using an estimated load of 20 pounds, the minimum factor of safety was calculated to be just below 2.

However, since Ansys is optimized for ABS thermoplastic, and PLA has a higher yield strength than ABS, the actual factor of safety is likely higher than the simulation suggests. The simulations applied a 25-pound force to the load-bearing surface of the bracket, simulating the forces exerted by the rods. Figure 8 shows the bracket with the applied loading surface.

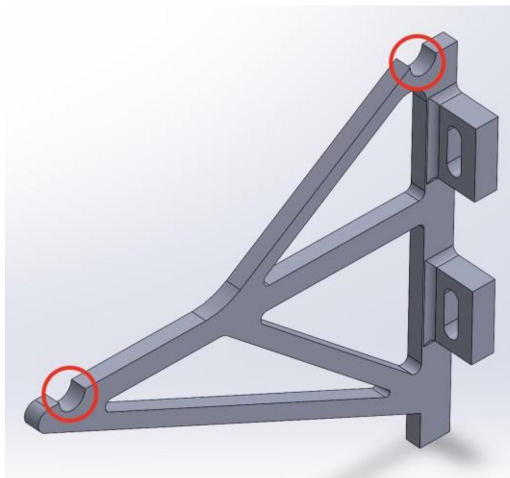

Figure 8: Bracket with circled loading surface.

Simulations for total deformation, equivalent stress, elastic strain, and safety factors for Version 4 of the bracket are shown in Figures 9-11, all indicating values well within acceptable limits.

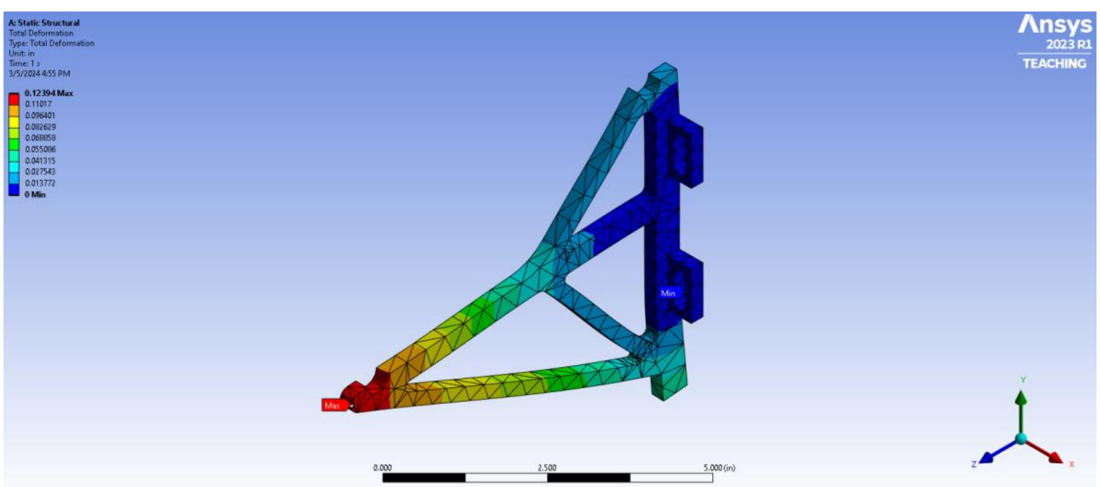

Figure 9: Total Deformation (Version 4).

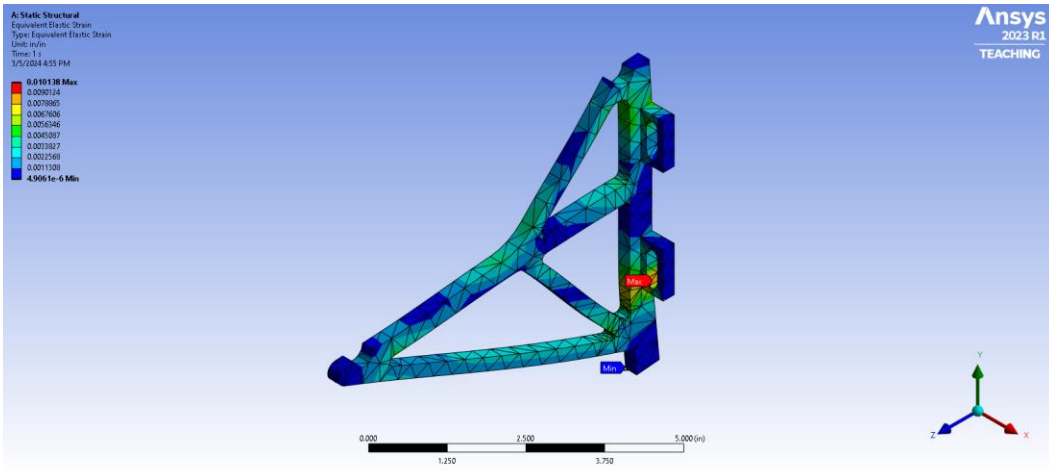

Figure 10: Equivalent Elastic Strain (Version 4).

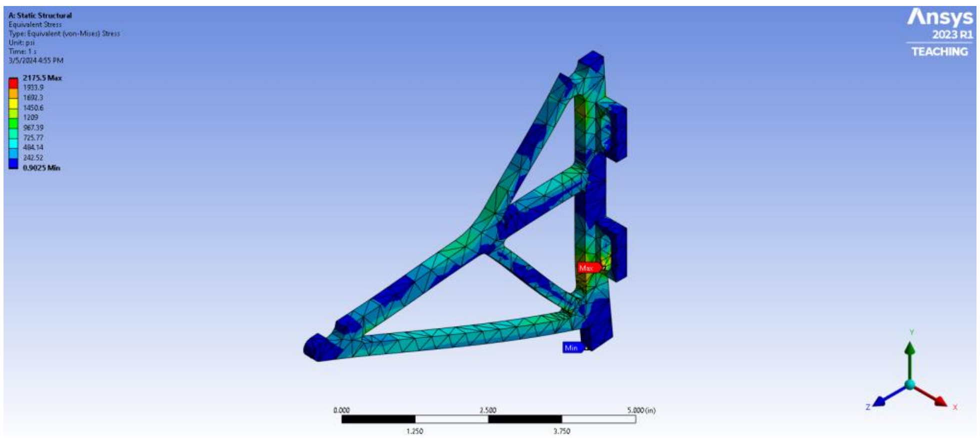

Figure 11: Equivalent Stress (Version 4).

3D-Printed Physical Bracket Testing

Physical testing was conducted on the 3D-printed brackets to assess their real-world performance. The brackets were subjected to instantaneous failure testing and fatigue failure testing. Figure 12 shows the setup for testing, where the bracket was fixed to a beam, and a weight hanger was used to apply load.

Figure 12: Clamped Bracket (V3) with hanger off the end.

In the first round of testing, each bracket was loaded incrementally until failure occurred.

Figure 13 shows the first failure at 31.2 lbs, with the bracket breaking at the mounting tab.

Figure 13: Test 1 Mounting Tab Failure.

After repositioning the clamps, the second test resulted in failure at the central intersection of the struts, as shown in Figure 14.

Figure 14: Test 2 Central Intersection Failure.

After further refinement of the bracket design, Version 4 was tested and demonstrated improved weight-bearing capacity. Version 4 was holding 36.2 lbs without failure, and failure occurred only at 46.2 lbs, a substantial improvement over previous versions. Fatigue testing was conducted on Version 4 by applying and leaving weight on the bracket for extended periods. The bracket was starting to bend and warp due to the applied weight.

Bracket Testing Results

Based on the results of both Ansys simulations and physical testing, the geometry of the rod bracket was modified to improve load distribution. Initially, the design relied on a single strut to support both rods in tension. The final design features multiple struts, including one in compression, to better handle the load.

Figure 15 show the identified weak points in the original design and the reinforced version with added support.

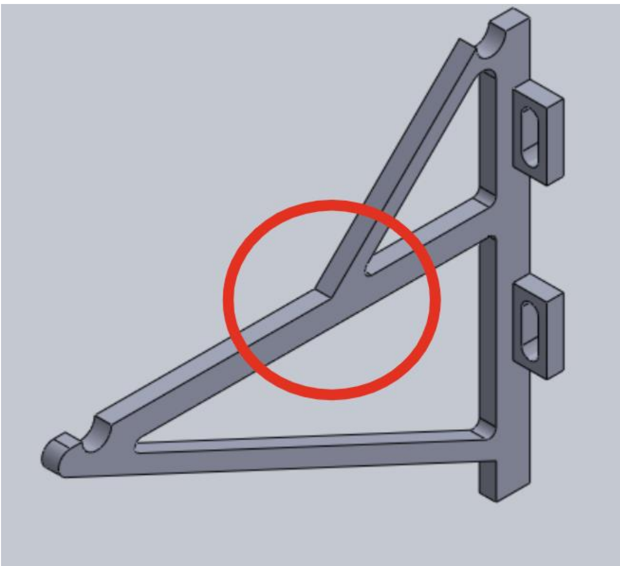

Figure 15: Rod bracket (V3) with weak point circled.

Prototype Irrigation Testing

The prototype design required several modifications to ensure proper functionality of the irrigation system. After trial and error, the team successfully connected the tubing and set up the recirculated watering system. Figure 16 shows the initial tests with the system in operation. The team ensured that the submersible pump could provide sufficient pressure to push water to all the nozzles and that the water was recirculated back to the tank.

Figure 16: Prototype irrigation tests.

Prototype irrigation test (close-up) shows the system with plants and substrate in place, demonstrating that the water flowed as intended, with each pot receiving appropriate irrigation.

Project Validation and Current Status

The validation of the Plant Wall project began with approval from the Director of University Aesthetics and Campus Design, following several discussions to address concerns regarding the design's safety and aesthetic integration with the building's structure. The team ensured that the structural integrity of the frame and base was prioritized, incorporating solid materials and applying principles of statistical analysis to verify the design’s durability and performance.

One of the key objectives of the design was to ensure that the modules could accommodate a variety of plant species. This flexibility was achieved through a columnar design with modular pot holders, which allowed for customization based on plant preferences [6, 7, 8, 9]. Throughout the project, students managed a strict budget and made key design decisions accordingly. Weekly logs and validation data confirmed system stability, with students iteratively resolving irrigation inconsistencies and sensor inaccuracies. Their autonomous control system functioned reliably with minimal maintenance, and the collaborative problem-solving approach reinforced critical engineering management skills.

Results and Collaborations

The project structure encouraged specialization by discipline: biology students managed plant selection, pest mitigation, and watering optimization, while engineering students led design iterations, material selection, and automation. However, overlap was encouraged. Biology students participated in physical testing and sensor validation, while engineering students attended biology meetings to understand plant behavior and environmental needs. This deliberate blending promoted interdisciplinary fluency and fostered respect across disciplines. Biology student participation was cocurricular, not formally assessed, which attracted students with intrinsic motivation and allowed for flexible, creative contributions.

The successful implementation of the project is evidenced by the completed installation of the plant wall, which was made possible through collaboration with several external vendors. Laser Engineering Forming (LEF) was instrumental in the manufacturing of the aluminum sheets required for the plant wall frame. LEF provided services such as laser cutting, bending, and painting, ensuring the accuracy and precision needed for the final product.

The plant wall base design incorporates features such as water catchment planters, a support structure, and an exterior façade for aesthetic purposes. The collaborative effort between engineering and biology students, despite being voluntary, has resulted in the development of an innovative solution, with feedback from both groups shaping the design and final outcomes. This base is integral to the overall project, as it houses the water reservoir for the irrigation system and provides the necessary structural support for the modules.

Throughout the design process, the team adhered to relevant standards to ensure that the project met engineering, safety, environmental, and botanical requirements. For instance, ASHRAE standards were consulted to ensure the plant wall system complied with acceptable indoor air quality and ventilation requirements. A moisture barrier was incorporated between the modules and the wall to prevent water damage, in accordance with these standards.

The team also followed the guidelines outlined by the American Society for Testing and Materials (ASTM), specifically ASTM D2488-17, for the classification of soils. This standard was critical in selecting the appropriate soil types for the vertical garden, ensuring optimal plant growth. The Biology Department provided expertise in plant care, further ensuring the project's success.

Significant improvements have been made by students to the Plant Wall project, particularly in strengthening the structure and optimizing the irrigation system. These upgrades were necessary to prepare the system for the integration of PASCO ST-2997 sensors for real-time data collection. These sensors are designed to monitor key environmental variables, such as soil moisture, temperature, and humidity, enabling the team to adjust irrigation levels dynamically [10]. By integrating these sensors, the irrigation system has become a Smart Irrigation System, which allows for real-time monitoring and water distribution based on plant needs. The sensors provide actionable data that is used to optimize water usage and ensure optimal plant growth. The integration of the PASCO ST-2997 sensors is a critical step toward automating the system, improving sustainability, and ensuring efficient water management. This data also informs the development of mathematical models that predict water requirements, contributing to the long-term efficiency of the system.

Challenges for Future Development

Despite the progress made, several challenges have emerged that will need to be addressed in future developments of the Plant Wall project. During an observation of the installed plant wall for about six months, it was revealed that the plants have been affected by several pest infestations, including spider mites, mealy bugs, and thrips. To mitigate the infestation, the team has purchased Imidacloprid (a systemic insecticide in granule form), which is intended to control the pests and restore plant health.

Were different aspects of the design process parceled out to different groups? How did you assess student performance? Further understanding of how student involvement was structured could help guide future iterations of the project, especially in terms of collaboration between the Biology and Engineering departments.

Further complicating matters, the irrigation system is facing issues with its water delivery. The length of the main pipe connecting the central water source to the individual pipes leading to the plants is excessive, which has resulted in reduced water flow efficiency. Additionally, the pipe that connects the plant wall to the clear glass tank below is difficult to maneuver, and is currently held together with duct tape. This connection is critical for filtration and monthly treatments of the plant wall, and its current state is not sustainable.

Another significant issue is the malfunction of the right wall of the plant system, which has forced Biology Department to remove three vertical rows of plants. Additionally, the limited space (only 2 inches) between the plant wall and the supporting wall has raised moisture concerns, as there is no moisture barrier in place to prevent potential water damage to the wall and carpeted floor.

In an attempt to address lighting issues, Biology Department has purchased a Soltech full spectrum lighting system, which provides the plants with appropriate lighting for optimal growth. However, these challenges underscore the need for further refinement and modifications to improve the system's reliability and efficiency.

Recommendations

Moving forward, the team has identified potential solutions to address the pest infestation and irrigation issues. The Biology Department has recommended modifications to the plant wall to accommodate climbing plants. Two products—a tree fern substrate board and a vertical moss pole—have been identified for use in the prototype design. These additions will be tested for compatibility with the existing module design to determine if further modifications are necessary.

Additionally, the team is exploring the implementation of an electronic data collection system [3]. This system would integrate sensors such as moisture, pH, and light meters, connected to a Raspberry Pi microcontroller, to automate and optimize plant care. This technology would provide real-time insights into key environmental factors, enabling data-driven decisions regarding irrigation and nutrient delivery. The components for this system have already been procured, including a Raspberry Pi Pico, capacitive soil moisture sensors, and relays. The Raspberry Pi will process the collected data to improve resource efficiency and plant yields.

Furthermore, the team is considering expanding the modular design for different installation locations within the university. While some of the proposed sites were not pursued in this iteration, scaling up production and adapting the design for various spaces in the future remains a viable option.

Reflections and Impact

Faculty members noted that the Plant Wall Project significantly enhanced student engagement. One instructor reflected that “the interdisciplinary nature of the project challenged students to communicate across domains and adapt their knowledge to a shared purpose.” Student feedback was similarly positive, with one biology student commenting, “This project taught me more about how plants really work in different conditions than any textbook could.” Several students noted that failures, such as pests or poor irrigation in early designs, provided the most valuable learning moments—reinforcing scientific resilience and iterative thinking.

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