The Future of Engineering Education
2024 Annual Conference & Exposition
Oregon Convention Center
Portland, OR . June 23 - 26, 2024
ASEE
Paper ID #42727

The Thurman Botanical Tapestry: Integrating Engineering Design, Botanical Aesthetics, Scientific Innovation, and Pedagogical Enrichment

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Abstract

This paper presents the Thurman Botanical Tapestry project, focusing on its comprehensive definition of completeness in engineering. The project's core objective is the creation of a budget-compliant vertical plant wall equipped with an automatic plant care system, meeting specific criteria such as budget adherence, aesthetic enhancement of the building, structural integrity, and accommodation of diverse plant types for a visually pleasing impact.

The primary goal of the project is the meticulous design of a modular plant wall within stringent constraints, emphasizing the integration of nature into the academic environment. In addition, it encompasses the development of an indoor waterfall with a tribute to the university emblem, incorporating electronic readouts and monitoring systems for plant maintenance parameters, designed to be user-friendly for untrained student research assistants.

An essential aspect of this endeavor is the correlation between biological input factors and the success of the automated fertigation system. This involves constant monitoring of pH levels, sunlight intensity, and moisture content within plant pockets. The design of the green wall is tailored to biology student research assistants, ensuring intuitiveness and compliance with OSHA regulations. A mechanical system is also integrated to safely raise and lower plant modules.

Quality assurance procedures include virtual simulations and the operation of a mechanical prototype. Virtual simulations assess structural soundness, while the prototype trial run validates the irrigation system, checks for stress deformations, and monitors plant health. The final testing phase evaluates the functionality of the pulley system and the effectiveness of the indoor waterfall feature, harmonizing aesthetics, science, and engineering in a unique interdisciplinary project.

Introduction

The Thurman Botanical Tapestry represents a synergistic amalgamation of engineering design, botanical elegance and ecological inquiry, intertwined with educational innovation. Embellished with an array of Aroid flora, it functions as a dynamic, living laboratory, providing a conducive environment for students to delve into and comprehend the fundamental biological mechanisms intrinsic to their academic pursuits. This architectural engineering design installation not only furnishes practical insights into plant physiology, pertinent to domains such as bio-material engineering and pharmaceutical applications, but also enriches the pedagogy of engineering. Students harness their understanding of statics, materials science, and computer-aided design (CAD) to engineer a structurally sound framework conducive to optimal plant growth. Through experiential learning in machining and design, they acquire tangible skills transcending mere theoretical comprehension. The team composition include individuals from various disciplines such as engineering, botany, and industry. Students have actively participated in the design and construction phases, their contributions displaying their hands-on learning experiences and practical skills development. The project enhances student engagement, fosters interdisciplinary collaboration, and provides practical learning opportunities with skills acquired by students, such as critical thinking, problem-solving, and teamwork.

The multifaceted utility of the tapestry transcends its aesthetic and scientific dimensions, presenting an unparalleled platform for interdisciplinary exploration in engineering and botany. It is underpinned by a sophisticated network of sensors and research methodologies [1], [3], [4], presenting a unique design challenge in crafting a user-friendly system accessible to individuals with limited botanical acumen. The educational component of the project pivots on empowering students to actively engage in the upkeep of the botanical wall, bridging the chasm between theoretical knowledge and real-world application.

In consonance with the integration of technological tools in botanical pedagogy, previous studies underscored the pivotal role of innovative instrumentation in STEM education, exemplified by the Esque Box [2]. This paper elucidates the comprehensive approach imperative for such endeavors, encompassing streamlined maintenance protocols, remote monitoring capabilities, specialized training modules, knowledge dissemination mechanisms, feedback loops, and adaptive automation frameworks. Thus, it fosters a deeper appreciation of botanical life while cultivating ecological consciousness and stewardship.

Design

The Thurman Botanical Tapestry project at Oral Roberts University (ORU) constitutes a pioneering endeavor aimed at erecting a vertical botanical wall that seamlessly integrates with the architectural ambiance of the university's edifice while adhering to stringent budgetary constraints. The project's triumph hinges upon the fulfillment of several pivotal criteria that delineate its comprehensive nature.

Primarily, the design imperatively conforms to the financial stipulations set forth by the department, ensuring the project's viability and sustainability within the allocated resources. Secondly, the endorsement of the design by the head of ORU's interior design department is indispensable, affirming its augmentation of the edifice's visual allure, thus accentuating the project's dual functionality and aesthetic enhancement of the spatial milieu.

Structural integrity stands as another pivotal facet of the design paradigm. The tapestry necessitates robustness to accommodate a diverse array of plant species, including canopy, climbing, and broadleaf varieties, essential for imbuing the space with a nuanced texture and aesthetic profundity, thereby metamorphosing it into a dynamic, living artwork. Moreover, the design mandates the integration of an automated plant care system, comprising electronic sensors or readouts for monitoring pivotal parameters crucial to plant health and maintenance, such as soil moisture, light intensity, and nutrient levels, epitomizing the project's innovative fusion of botanical expertise with contemporary engineering solutions.

The fabrication of the Thurman Botanical Tapestry entailed meticulous strategic planning and precise execution. Commencing with the selection of a spectrum of resilient and aesthetically pleasing Aroid plants, the project's structure was meticulously engineered to accommodate the varied growth habits of these botanical specimens while seamlessly incorporating cutting-edge sensor technologies. These technological enablers played a pivotal role in real-time monitoring of critical environmental parameters, including humidity, temperature, and light intensity, ensuring optimal growth conditions. Furthermore, the project's methodology encompassed the formulation of standardized maintenance protocols aimed at perpetuating plant health and preserving the tapestry's aesthetic allure.

Moreover, the project's maintenance regime, encompassing the upkeep of the structure, plants, and automated systems, is engineered to be readily manageable by student research assistants, irrespective of their engineering acumen, thereby infusing an educational dimension into the project, facilitating hands-on learning experiences and fostering practical proficiency in plant care and system maintenance.

Background Analysis

The development of innovative engineering projects often draws inspiration from existing patents and technological advancements. In the realm of vertical gardening, patents related to plant wall structures and irrigation systems provide valuable insights that inform the design and implementation of such projects. This analysis explores the influence of relevant patents on the design and development of a vertical botanical wall project, focusing on concepts such as trough-based plant containment, structural integrity evaluation, and efficient irrigation methods. By integrating findings from these patents, the project aims to optimize spatial utilization, ensure structural stability, and enhance plant growth through effective fertigation techniques. This investigation underscores the significance of leveraging existing intellectual property to inform and enrich engineering endeavors, ultimately contributing to the advancement of innovative solutions in botanical engineering.

The patent entitled "Vertical Garden," depicted in Figures 1 a and b, introduced the innovative concept of employing troughs for the containment and support of plants, diverging from the initial notion of utilizing 3D-printed pots. This transition to troughs represented a pragmatic shift, aligning with practical considerations such as cost-effectiveness and ease of manufacturability. While the patent served as a catalyst for inspiring certain aspects of the project, the project evolved further to incorporate vertical troughs to optimize spatial utilization and plant arrangement.

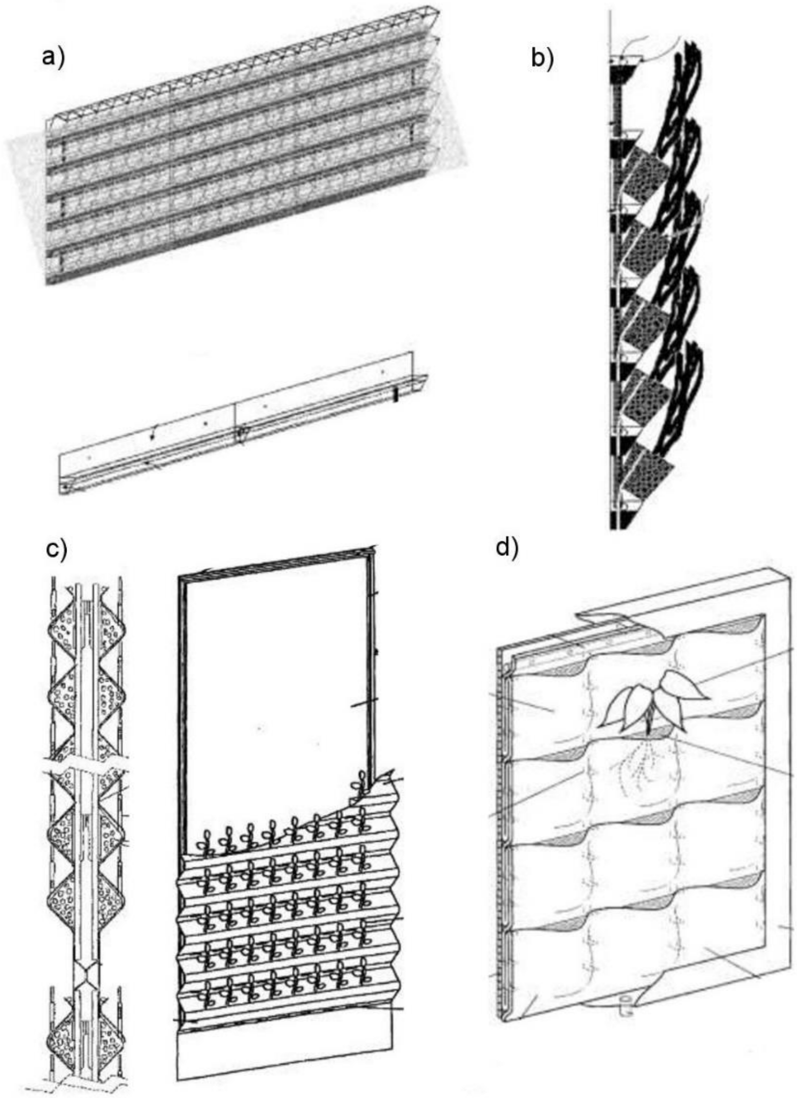

Figure 1: Patents: a) Vertical Plant Wall [9]; b) Vertical Plant Wall [10];

c) Felt Pocket Design Patent US8141294-B2 [12]; d) Chinese patent CN101553108B [11].

The meticulous examination conducted within the patent regarding the weight distribution and structural elements of vertical plant walls exerted a profound influence on the project's design ethos. As a result of this thorough structural integrity assessment, the project team engaged in extensive deliberations concerning the chosen design's load-bearing capacity and weight distribution. A comprehensive plan involving a series of ANSYS simulations and pertinent testing methodologies will be employed to ensure that the project's design offers unparalleled stability and safety.

In the realm of plant wall fertigation, Patent US8141294-B2 (Figures 1 c) was scrutinized to gain deeper insights into vertical garden irrigation techniques and mechanisms for channeling gravity-driven water flow to felt plant pockets to ensure optimal saturation. This design encompasses felt pockets equipped with bottom channels designed to accumulate and direct surplus water to the recirculation reservoir, thus augmenting the understanding of the absorptive properties of felt plant pockets and guiding the development of optimal water collection systems.

For additional insights into the design aspects concerning plant pots with irrigation, the Chinese patent CN101553108B was consulted (Figures 1 d). The incorporation of bent aluminum troughs not only contributes to minimizing the overall weight of the design but also reduces the exposed metal surface area not covered by plants. Additionally, the bends in the troughs facilitate efficient substrate retention, promoting conducive conditions for robust plant growth while optimizing spatial efficiency.

In conclusion, the analysis of patents related to vertical gardening has provided invaluable insights that have profoundly influenced the design and development of the botanical wall project. The transition from 3D-printed pots to troughs for plant containment, inspired by patents such as US8141294-B2 and CN101553108B, reflects a strategic shift toward cost-effective and manufacturable solutions. Moreover, the structural integrity evaluation guided by patent findings has informed critical decisions concerning load-bearing capacity and weight distribution, ensuring the project's stability and safety. Additionally, insights gleaned from patents concerning efficient irrigation methods have facilitated the design of systems that optimize water usage and promote healthy plant growth. By leveraging existing intellectual property, the project has been able to integrate cutting-edge technologies and methodologies, ultimately advancing the frontier of botanical engineering. Moving forward, continued collaboration with patent holders and ongoing research into emerging technologies will further enhance the project's efficacy and contribute to the broader field of vertical gardening and engineering innovation.

Analyzing concepts from these patents alongside the team's own innovations, three potential designs have been formulated and presented to the biology department leadership. Each design addresses the project's requirements uniquely, presenting both advantages and drawbacks. The initial design proposed for this undertaking comprised four vertical metal frames supporting two modular plant panels measuring 6 by 6 feet. These panels were intended to be maneuvered via a winch-and-pulley system and secured within the metal frame via roller tracks, both vertically and horizontally. The dimensions of these panels underwent iterations during the developmental phase, varying from 6 by 6 to a final dimension of 3 by 6 feet, facilitating effortless removal from the tracks when necessary. The fundamental concept of an external frame and pulley mechanism remains consistent across all three designs, with the primary engineering challenge revolving around optimizing the arrangement of plant compartments within the modules (Figure 2).

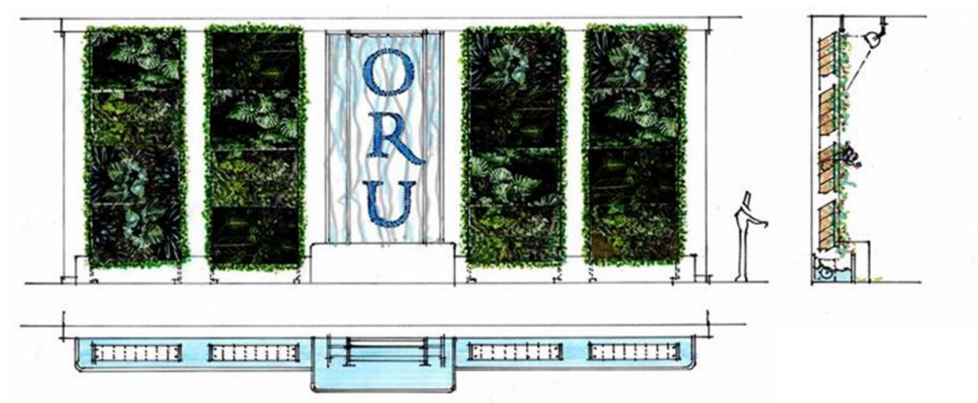

Figure 2: The Botanical Tapestry Architectural Drawing.

In the first design, the plant compartments within the modules are horizontal troughs. These troughs would be made of bent aluminum and welded or bolted onto a metal back plate. This design is simple to manufacture and irrigate as the water can filter down each trough and water the next row through holes in the bottom.

Design 2 is the Biology department's accepted final concept before entering the development phase. This design contains the same vertical metal frame but with vertical rows created from vertical metal dividers and plastic inserts to create customizable plant compartments. This accommodates a more extensive range of plant types and creates a more plant-dense facade that eliminates visible metal paneling like Design 1. This design will require more effort to manufacture within the department’s time frame and some intelligent material choices to minimize the product's weight. These constraints play to the engineer’s strengths, which make it the wisest choice to begin development.

The final design was developed as a fail-safe option that operates within all the technical design constraints but does not uphold the aesthetic requirements given by the biology department. In this design, a metal panel of slots is the module's back panel. Inside these slots would hang plastic boxes. This is not the most aesthetic option, but it is the lightest in weight and the simplest to construct.

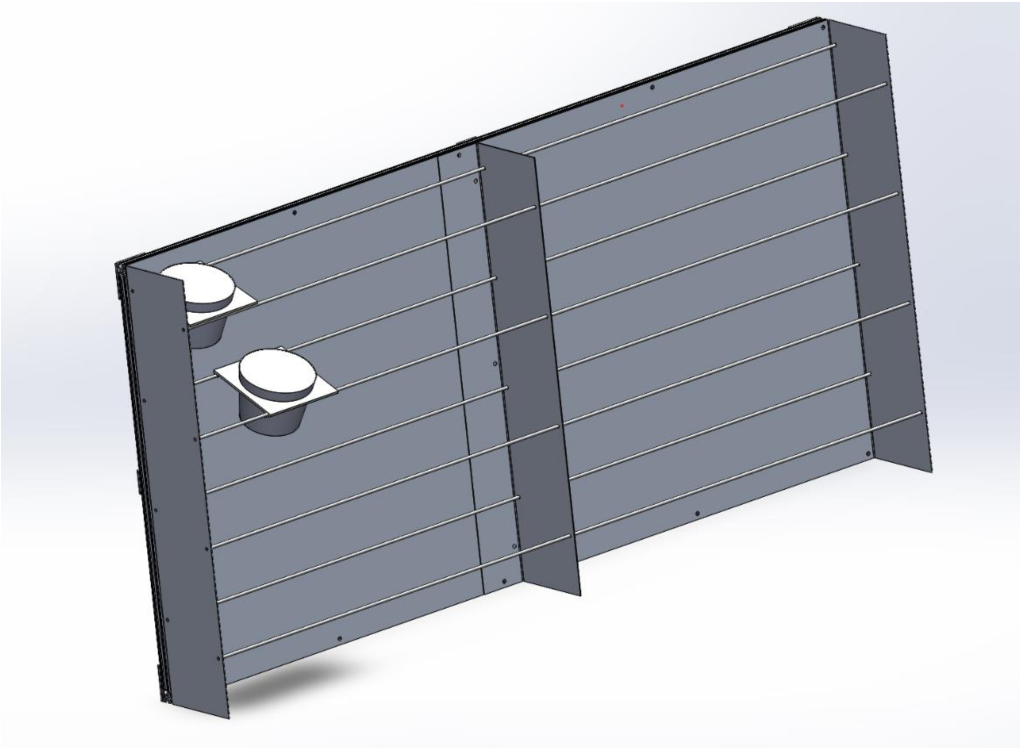

Figure 3: Interim 3D model of one module using the second design.

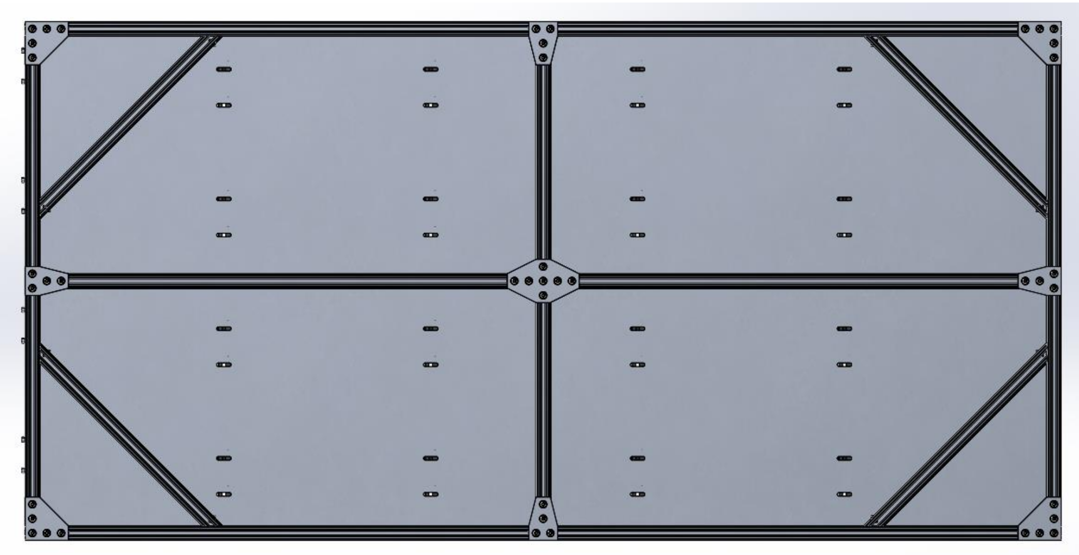

Figure 4: Framing of one module, including external and internal fasteners.

Figures 3 and 4 depict the 3D model of one module. The team is currently in the final stage of the design process. Minor details need to be included, and some flaws in the prototype function need to be addressed. The team had assembly, weight, and external forces in mind when producing a 3D model. Hand calculations and ANSYS simulations will overcome these challenges throughout the project. The team needs to understand what materials to use based on the physics and mechanics of the materials of the project structure. This is mainly due to the moisture introduced by plant irrigation, as well as the ability of the structure to function in a long-term capacity.

The design process for this project involves navigating through various design constraints encompassing qualitative and quantitative considerations. While aesthetics contributes to the subjective appeal of the project, the primary purpose of engineering study lies in the design of a structure with great weight-bearing capacity and structural integrity required to support the plants in different states – fully saturated with water or in a dry condition. In collaboration with the biology department's recommendations, a comprehensive estimation was made for the maximum weight of a fully saturated plant, encompassing the pot, substrate, plant matter, and unabsorbed water, resulting in a limit of 7 pounds per plant container.

This weight estimation forms the basis for critical design parameters, shaping the components' specifications. The 3D printed brackets, for instance, must be engineered to support a maximum load of 7 pounds each, while each row of aluminum rods needs to withstand 70 pounds. Further up the hierarchy, each module must weigh 280 pounds.

The design approach is centered around accommodating 10 pounds per plant or 400 pounds per module to ensure a reasonable safety factor. This consideration not only adheres to safety standards but also provides the robustness of the overall structure. Despite the challenges encountered during ANSYS structural simulations for larger assemblies, a topic that will be delved into later, the simplicity and insightfulness derived from the simulations of the 3D-printed brackets are worth noting. These simulations provide valuable insights into the performance and reliability of these components, paving the way for informed decision-making in the subsequent stages of the design process (Figures 5, 6).

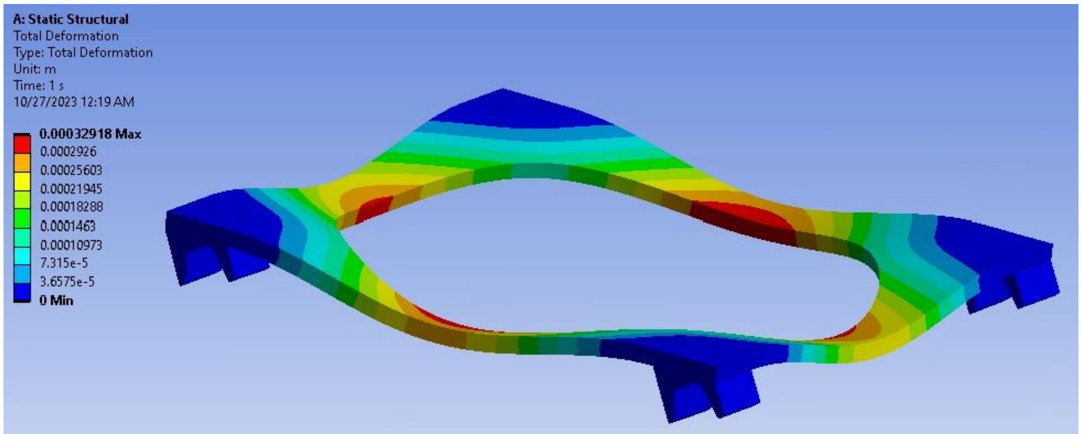

Figure 5: Ansys Simulation of Total Deformation.

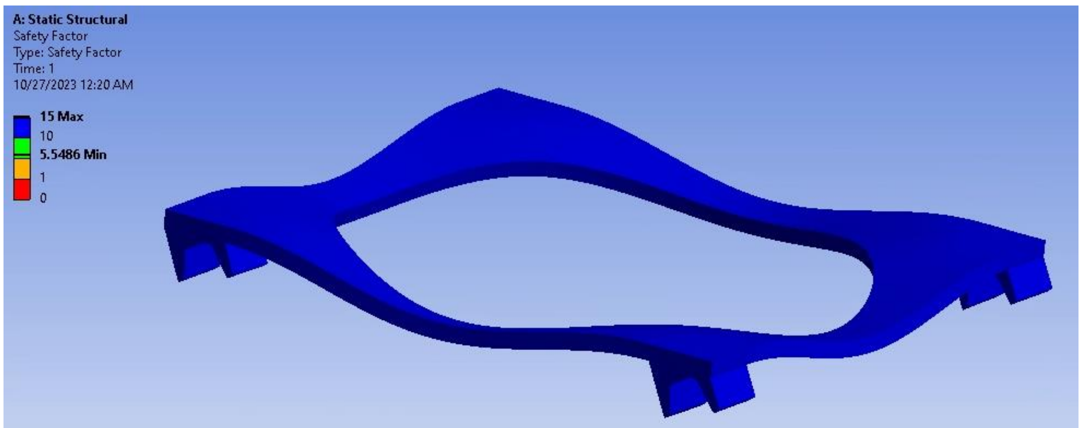

Figure 6: Ansys Simulation of Safety Factor (Pot Holder).

A force of 7 pounds was applied to the inside circular surface. These Ansys simulations are related to our previous design of the pot holder brackets. It was slightly modified to create a clip-like function at the corners. This should not change the deformation or safety factor enough to need to recalculate it. The material is the same, and the overall dimensions are the same. The simulations show that the plastic is strong enough to support this weight. Figure 6 shows that the minimum safety factor is over 5.5, which falls well within the constraints for this project.

A bracket was also designed to hold the horizontal rods and reduce bending from the weight of the plants. These will be 3D printed in a nylon fiber filament, offering greater longevity and moisture resistance than a traditional PLA filament.

An Ansys structural simulation was conducted on these brackets using an estimated 20-pound load. The minimum factor of safety was found to be slightly less than 2. However, the simulation package only supports the characteristics of ABS thermoplastic, not PLA or nylon. Nylon has a higher yield strength than ABS, so our factor of safety is likely higher than the simulation would suggest.

To get accurate theoretical results, the fixed support was attached to the inside of the mounting tabs to simulate the bracket being held up by bolts. A 25 lb force was then added to the inside of the load-bearing surface to simulate the force of the rods, as seen in Figure 7. This force was split like a triangle loading force. 16.67 lbs of force was added to the tip of the bracket, and 8.33 lbs was added to the top. The simulations were run on 3 versions for a bracket, Version 2-4. Version 1 was not tested because it was created before we switched to bolting the brackets in, making testing this version unnecessary.

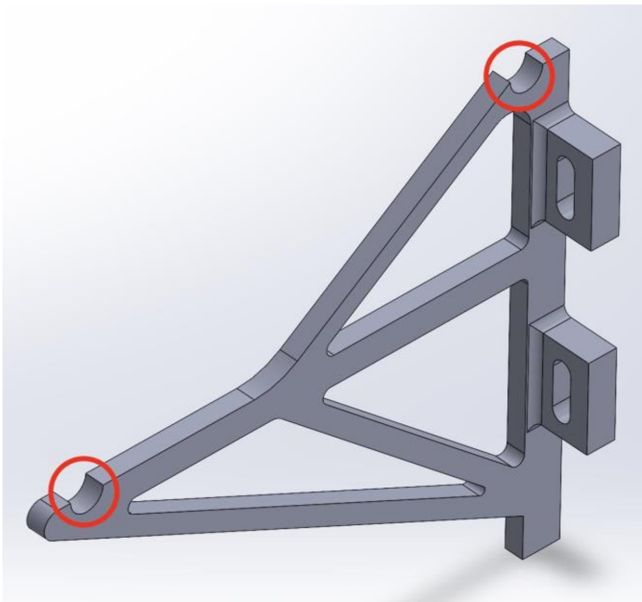

Figure 7: Rod Bracket Model.

The simulation tests included total deformation, equivalent stress, elastic strain, and safety factor. Figure 8 shows version 4 of the brackets in the simulated tests for the total deformation (a), equivalent elastic strain (b), and equivalent stress (c). Every one of these values is well above the necessary amount.

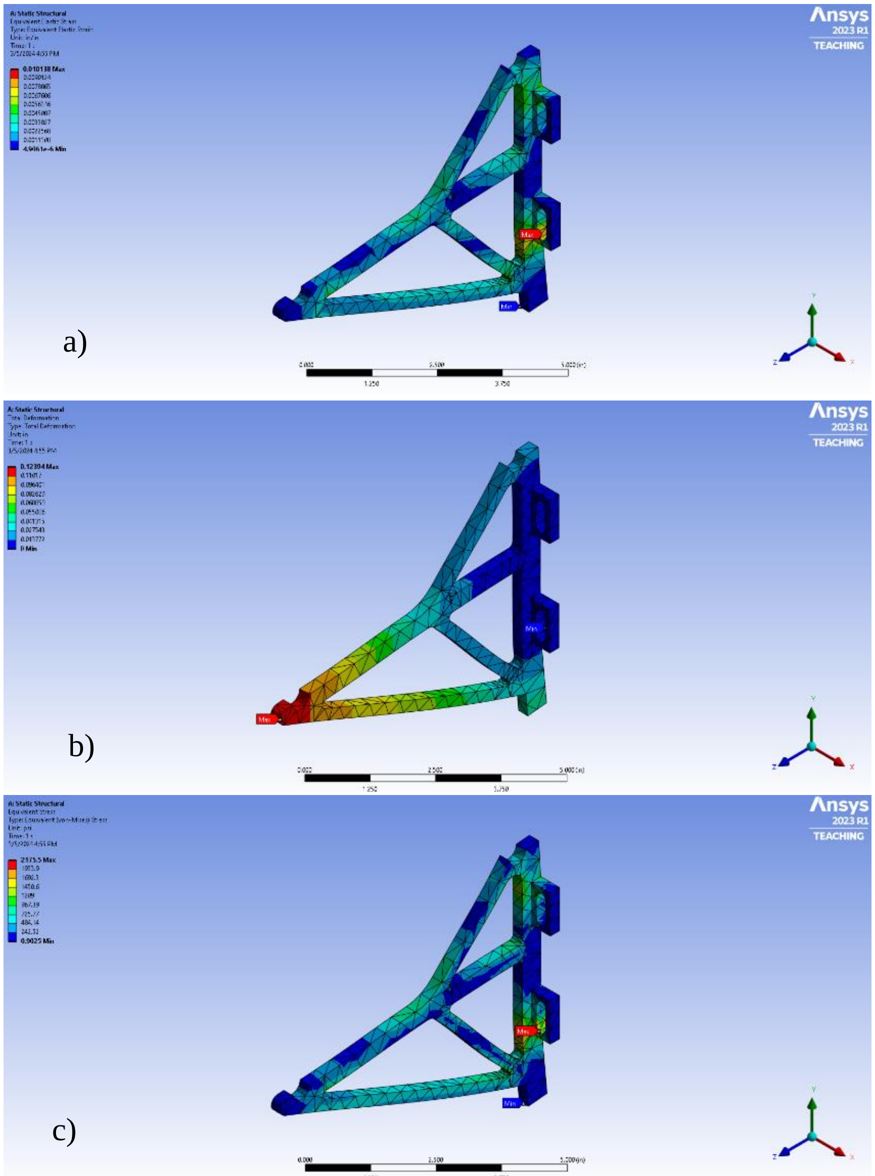

Figure 8: Ansys Simulation tests of the brackets version 4 for:

a) total deformation Version 4 (Units: in); b) equivalent elastic strain Version 4 (in/in);

c) equivalent stress (psi).

However, one of the most essential simulated tests is the safety factor. The simulations showed that the safety factor improved after each iteration of the bracket. For version 1, the minimum factor of safety (SOF) is 1.1705. For version 2, it is 1.2082, and for Version 3, it is 1.8294. These SOF values are much higher in the actual model because of the increased tensile strength and density. All of this data helped point toward the structural integrity of the module design.

Physical testing

The design of the 3D-printed pot holder included the ability to hook onto the rod that runs through the whole module. Because it takes a bit of force to pull the pot holder off the rods, a force gauge was used to measure the force it takes to pull the pot holder off. It uses tape and the hook connected to the force gauge, as seen in Figure 9.

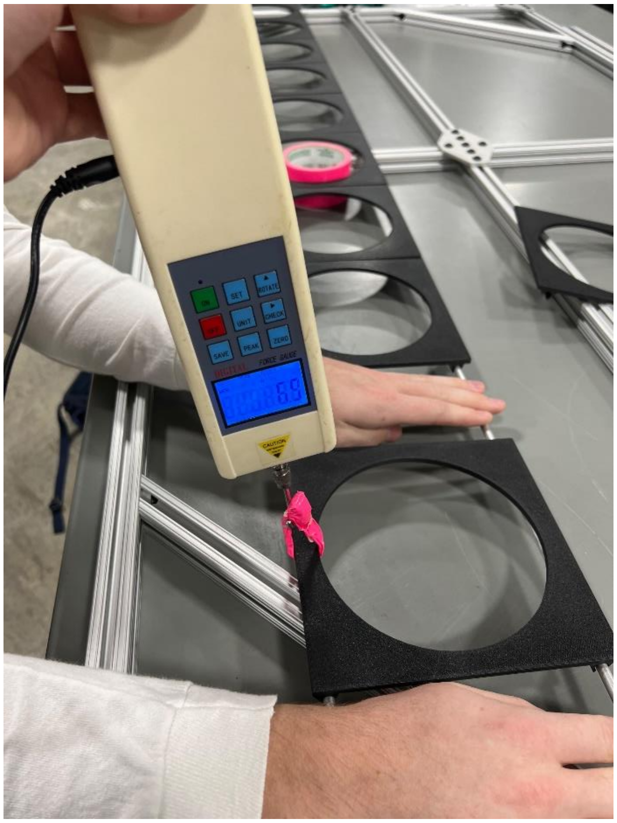

Figure 9: Measurement of the force using Force Gauge.

With this test, it is essential to consider the human error present in such experiments. The different angles at which force was applied, the position of the second person's hands holding the rods down, or the speed at which it was used could have all affected the results of this test. Any of these could have skewed the results. This culminated in a standard deviation of 2.57, which is higher than what is considered acceptable for data of this nature. Table 1 shows the data and the number of tests taken. Attempts 6 and 7 were taken out of the results as outliers with values of 21.4 and 20.5 Newtons. These would have been a full 7N lower than the average force of 27.972N.

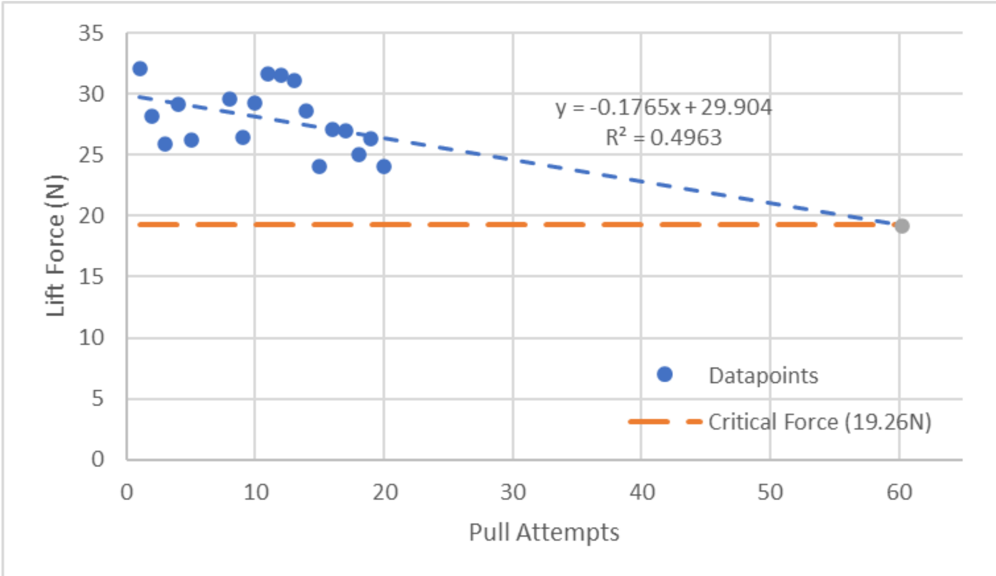

Figure 10: Force vs attempts graph.

This graph (Figure 10) shows the spread of the data, which is backed up by the standard deviation. However, valuable information can still be taken from the graph. The graph shows that the linear line is downward trending. This shows the force it takes to pull off the pot holders slowly decreases over time due to the deformation of the plastic used.

It also shows the calculated impending/critical force and what attempt that would happen on. This data is important in terms of cycle life of the pot holders. This weight that is calculated is with plants and other material needed within the pots and the pot holders. All this data is relevant to the complete understanding of the time it would fail if everything was ideal and was properly operated.

In Figure 11, there is a free-body diagram of the pot holder in a side view, and the external forces acting upon the body in the instance of a force pulling the holder straight up off the rods. We have included the normal force of the holder's mass and the force of gravity acting on the center of mass of the plant holder, and the force of the clips resisting the operator's action to remove the holder from the rods. This force has been termed "impending force", as this instance is not a constant force being acted upon the body, but only at the impulse of an operator. Additionally, for this purpose, the angle at which the holder is mounted on the prototype is estimated to be 30 degrees.

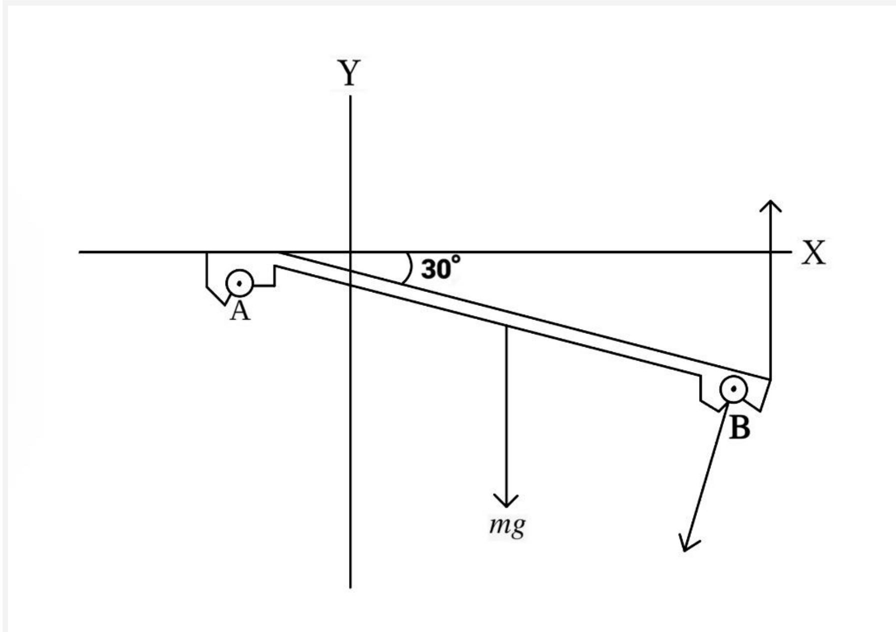

Figure 11: Free Body Diagram for Impending Force

Calculations

$$mg = 5lb \cdot F = 22.24N$$

$$(mg)cos\theta = Impending\ Force \quad \text{(Equation 1)}$$

$$\theta = 30°$$

$$(22.24N)cos(30°) = 19.26N$$

$$y = -0.1743x + 29.904 \quad \text{(Equation 2)}$$

$$y = 19.26N$$

$$19.26 = -0.1743x + 29.904$$

$$x = 60.31 \ Iterations$$

$$Iterations \ per \ year = 8$$

$$\frac{60.31 \ Iterations}{8 \ Iterations \ per \ year} = 7.54 \ Years$$

The manufacturer of the PLA plastic that we are using gave it a 12-18 year life time. We assumed before our calculations that the PLA would not last as long. This is because of many other factors acting on the plastic like water, human error, overuse, etc. This goes directly with our calculations which confirms the team's assumption of it not lasting as long as the manufacturer describes. We calculated it would last 7.54 years before inoperable damage would occur.

Figure 12: Module Prototype and cart with Plants.

PROTOTYPE DEVELOPMENT

A single module prototype was constructed alongside a mobile stand and cabinet to provide a test platform. This was made to showcase the original design and make it easy to move around if needed. The prototype consists of a single plant wall module mounted on a wooden rolling cart. The cart was designed to house and store a standard-sized water tank and other miscellaneous troubleshooting components (Figure 12).

This module supports the irrigation of up to 32 plant pots and includes an automatic pump timer and adjustable nozzles for drip or spray. When turned on, it takes about 10 minutes to thoroughly saturate all four tiers of plant pots with water and drip into the recollection drain. This prototype will allow the users of the plant wall to become familiar with its functionality at a more usable height. It also allows the plant managers to gain experience preparing and caring for plants in this new botanical area.

While constructing the prototype, several oversights in the initial design were noticed and will be corrected in future designs. For example, the positions of the horizontal rods didn't allow the plant pots to sit into the pot holders fully. This was because of human error when hand-drilling the holes on all three vertical panels. The design was revised spontaneously during construction and then carefully re-designed afterward. Additionally, due to flaws in the positions of the holes for the rods, the prototype can only hold eight pot holders on each side instead of the intended 10. With more careful fabrication, possibly using CNC-assisted tools, the rods should allow all ten pot holders to fit correctly across the length.

Another complication when constructing the prototype was the design of the wood stand. This was not designed before the construction of it. This posed a problem when sourcing the materials. We had an idea in mind but never put it on paper, which made it more challenging to build. This taught us to make sure to put on paper or 3D software everything that goes into the project so that we know a closer estimate of materials. It turned out to work after consulting with an experienced woodworker.

Finally, the irrigation system was carefully put together piece by piece. The submersible pump was tested to ensure enough head pressure to make up the whole module and the stand. Then, a few brass fittings merged the smaller tubing and larger hose down to size from 1/16 inch to 3/4 inch. This was a challenge, but eventually worked out and was made possible. Then, the nozzles were connected to the smaller tubing by T-joints and heated up with a heat gun to make the tubing more malleable for an easier fit. This worked as planned; the water drips or prays depending on the user's liking. The system also recirculates with a drain going down to the tank where the pump is. This is the best way to conserve water and keep the nutrients within the system.

Conclusions

1. The Thurman Botanical Tapestry epitomizes the harmonious fusion of artistry, scientific inquiry, and technological innovation. Beyond enhancing the visual allure of the Biology Department at the university, it assumes the pivotal role of a living laboratory, enriching the academic experience for students. This endeavor lays the groundwork for further exploration into the realm of interactive botanical installations, shedding light on their potential utility in educational and urban landscapes.

2. Since its inception, the Tapestry has exhibited remarkable growth and vitality, underscoring its efficacy as a botanical marvel. Leveraging a sophisticated sensor network, it has yielded invaluable data on environmental dynamics, elucidating critical parameters conducive to optimal plant development. The robust health and vigorous growth patterns observed in the plants underscore the efficacy of the tapestry's design and maintenance protocols, epitomizing a symbiotic relationship between technological prowess and botanical prowess in an educational milieu.

3. Functioning as a dynamic educational instrument, the Tapestry stimulates curiosity and engagement in the realms of botany and environmental science among students. By seamlessly integrating technology with natural elements, it engenders a distinctive learning environment where theoretical botanical concepts manifest in real-time observations. Moreover, this project unveils the potential for analogous installations in urban settings, presenting a pragmatic pathway to incorporating verdant spaces within contemporary infrastructural frameworks.

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