Toward Intelligent PlantWall Systems: An Engineering Multidisciplinary Educational Project for Sensor Integration and Automation

Dr. Pavel Navitski, Oral Roberts University

Dr. Pavel Navitski is Associate Professor at Oral Roberts University from 01/2020 after a stint as a Fulbright Visiting Scholar at Oklahoma State University, where he was researching drift detecting using sensor systems for field spraying and guest lecturing. He is originally from Belarus, where he was the head of the department of agricultural machines at the Belarusian State Agricultural Academy. The Belarusian State Agricultural Academy is where he earned his B.S., M.S. and Ph.D. degrees. Dr. Navitski's professional interests are mostly in modern agricultural machinery: setting the main types of agricultural machines for quality work; device features of configuration of new agricultural machinery; perspective cropping systems; precision agriculture; modern machines for chemical plant protection; renewability and bio-energy. He represents Oral Roberts University at ASME and Tulsa Engineering foundation.

Rachel L Budavich, Oral Roberts University
Simeon Spiess

Senior at Oral Roberts University studying engineering with a mechanical concentration

Dr. Elena Gregg, Oral Roberts University

Dr. Elena G. Gregg is a Senior Professor of Physics at Oral Roberts University, where she has taught since 2006. She holds an M.S. in Theoretical and Applied Spectroscopy from St. Petersburg State University and a Ph.D. in Optics from the State Optical Institute, Russia . Her research background includes molecular spectroscopy and light–matter interactions, with current scholarly work focused on experimental physics education and cosmic ray cascade investigations in undergraduate laboratory settings. Dr. Gregg is an active member of the American Society for Engineering Education (ASEE) and the American Association of Physics Teachers (AAPT), and she has contributed extensively to advancing physics pedagogy through curriculum development, laboratory innovation, and student-centered research experiences . She has co-authored multiple conference presentations on cosmic ray cascades and experiential learning, and her work has been recognized with an Honorable Mention Best Paper Award at the ASEE Midwest Section Conference. In addition to her teaching and research, Dr. Gregg is deeply engaged in service, including curriculum advisory roles for the Oklahoma Office of Educational Quality and Accountability and mentoring undergraduate engineering and pre-med students. Her recent work integrates environmental factors into cosmic ray detection experiments, enhancing hands-on learning in modern physics laboratories.

Toward Intelligent PlantWall Systems: An Engineering Multidisciplinary Educational Project for Sensor Integration and Automation

Introduction: From Smart Irrigation to Intelligent PlantWall Systems

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. 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 PlantWall project at Oral Roberts University is a multi-year interdisciplinary educational initiative that integrates engineering and biology through the design, deployment, and continuous evolution of a living laboratory. By April 2025, the project had achieved a fully functional smart irrigation system featuring modular mechanical structures, passive and active water delivery, filtration, and initial sensor-based monitoring. These developments were documented in [1,3], which emphasized system construction, reliability, and operational performance.

The current phase of the project represents a deliberate pedagogical and technical shift. Rather than extending mechanical design or duplicating prior irrigation strategies, the 2025–2026 iteration focuses on automation, computational modeling, and algorithmic decision-making. The PlantWall now serves as a platform for exploring sensor-driven control, data acquisition pipelines, and early-stage intelligent system design. This paper documents that transition and examines how automation-focused development supports student learning in embedded systems, control theory, and interdisciplinary problem solving. Similar sensor-based irrigation systems have been widely studied in agricultural engineering, demonstrating the effectiveness of feedback-driven control and embedded system integration [11,12].

This study is guided by the following research questions:

1. How does the transition from rule-based irrigation to sensor-driven algorithmic control affect system performance and reliability?

2. What challenges arise when implementing real-time sensing and control in a vertically distributed irrigation system?

3. How does participation in a multi-year, interdisciplinary system impact student learning in engineering and data-driven decision-making?

Educational Context and Course Integration

The 2025–2026 PlantWall project is embedded within senior-level engineering coursework, including instrumentation, controls, and design, while maintaining active collaboration with the Department of Biology. Students engage with real hardware, software, and biological constraints rather than simulated environments alone. The use of hands-on, project-based learning aligns with established STEM education practices emphasizing early exposure to real systems [2].

The PlantWall provides a physical context for abstract concepts such as feedback loops, sensor noise, calibration, latency, and threshold selection. Biology faculty contribute expertise in plant health indicators and environmental requirements, ensuring that engineering decisions are grounded in biological reality. This integration allows students to experience the interdisciplinary negotiation typical of real-world engineering systems. Since its inception, the PlantWall project has been intentionally structured as a longitudinal learning experience. In the first year, students addressed fundamental mechanical and biological challenges, including frame design, modular plant holders, and passive irrigation. Biology students selected plant species and established care protocols, while engineering students focused on manufacturability and structural stability.

The second year emphasized system refinement and dissemination. Irrigation efficiency and durability were improved, and the project was presented at regional and international conferences. By the end of this phase, the PlantWall functioned reliably as a smart irrigation system, capable of sustained operation in a public academic space.

The third year builds directly on this foundation. Students inherited an operational system and were required to understand, evaluate, and extend prior work. As documented in [10], this inheritance fundamentally altered the learning process: students began not with fabrication, but with system analysis, data interpretation, and goal reassessment. This continuity transformed the project from a build-focused experience into a systems-thinking exercise centered on automation and intelligence.

Student Team Structure, Roles, and Learning Scaffolding

Student roles during the semester naturally evolved based on interests and project needs. One group concentrated on mechanical redesign, addressing water capture inefficiencies through iterative gutter and tray concepts, as well as designing and testing multiple generations of sensor mounting brackets. Another focused on software and data acquisition, rebuilding the PASCO programming environment, learning SPARKvue and Blockly, and establishing a reliable sensor communication framework.

Importantly, these roles were not isolated. As noted in [7], students routinely cross-trained, collaborated in the machine shop, and jointly evaluated system limitations. Faculty involvement was intentionally advisory, guiding students through goal refinement rather than prescribing solutions. This scaffolded autonomy supported progressive ownership of the project.

Educational Research Methodology

Participants included senior engineering students enrolled in EGR 498/499 and collaborating biology students. Data sources included: weekly progress reports, final technical reports, instructor observations, system performance outcomes. Assessment was qualitative and based on: student reflections, observed problem-solving behavior, ability to transition from rule-based to system-level thinking. No formal IRB-based human subject research was conducted; the project functioned as a course-based educational activity.

Transition from Rule-Based Irrigation to Algorithmic Control

Earlier versions of the PlantWall relied on fixed schedules and simple threshold logic for irrigation. During the current semester, students critically reassessed these approaches. Meetings with faculty and prior team members revealed that full automation without sufficient data would be unreliable and pedagogically premature.

As a result, the project shifted toward algorithmic control informed by sensor feedback rather than predefined timing. Students began developing decision logic that accounts for moisture thresholds, temporal delays, and sensor variability. This transition represents a conceptual milestone: irrigation became a control problem rather than a mechanical task, reinforcing systems engineering principles.

Sensor Architecture and Data Acquisition Pipeline

The sensor suite deployed during the semester includes soil moisture, temperature, and humidity sensors connected through the PASCO platform. As described in [1,3], students prioritized understanding sensor behavior, installation constraints, and calibration procedures before attempting automation. Sensor calibration and reliability became critical aspects of system development. During testing, resistive soil moisture sensors exhibited corrosion due to prolonged exposure to moisture, leading to unreliable readings.

Different sensor types were evaluated during development, including resistive and capacitive moisture sensors, as shown in Figure 1.

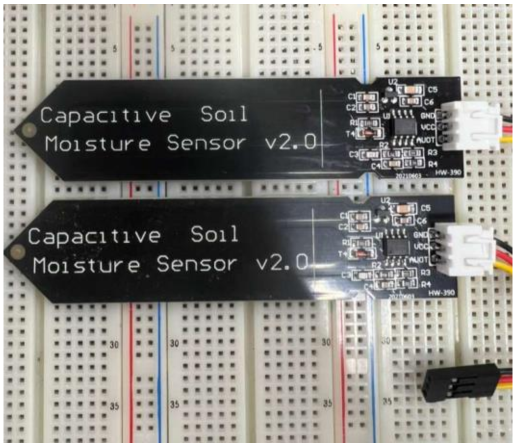

Figure 1. Soil moisture sensors used during testing (resistive and capacitive types)

The transition to capacitive sensors significantly improved measurement reliability and system durability.

The overall system architecture integrates sensing, control, and actuation components into a closed-loop irrigation system. As shown in Figure 2, soil moisture sensors provide input to the Arduino controller, which processes the data and activates the pump through a relay system.

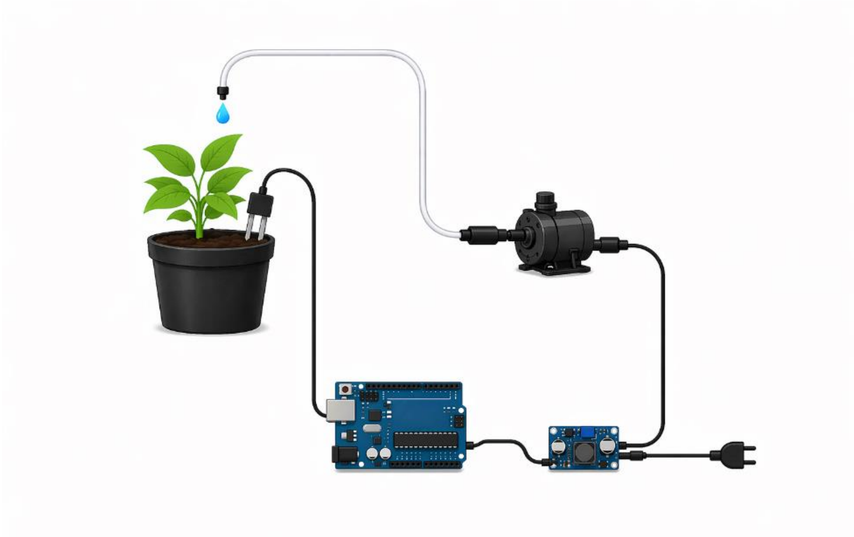

Figure 2 System architecture of the Arduino-based irrigation and sensing platform

This architecture enables real-time feedback control and allows the system to respond dynamically to environmental conditions.

As a result, capacitive sensors were selected and modified using protective enclosures and silicone coatings to improve durability. Sampling frequency was also adjusted to reduce sensor degradation and minimize noise. When multiple sensors were deployed simultaneously, they exhibited minimal deviation, indicating acceptable consistency for system-level control. The selection of environmental sensors follows established approaches for monitoring plant condition in precision agriculture systems [4,13].

The initial system relied on a PASCO-based sensing and control platform, shown in Figure 3.

Figure 3. Greenhouse Sense and Control Kit (PASCO ST-2997)

While this system provided an accessible starting point, it was limited in scalability and control flexibility.

Data acquisition was first validated on a miniature biosphere setup before scaling to the prototype PlantWall. This staged approach allowed students to isolate variables, identify noise sources, and confirm repeatability. Sensor calibration and placement became learning experiences rather than background tasks, highlighting the complexities of real-world data collection.

Environmental simulation capabilities were also explored using PASCO equipment, as shown in Figure 4.

Figure 4. Simulation of Sunlight Using the Greenhouse Sense and Control Kit

These tools allowed students to understand environmental variables before implementing full system integration.

During testing, resistive moisture sensors exhibited degradation due to oxidation, leading to unreliable readings. This issue necessitated a transition to capacitive sensors, which were further enhanced through protective enclosures and silicone sealing to improve durability in high-moisture environments. These modifications significantly improved sensor reliability and enabled consistent data acquisition.

Computational Modeling and Algorithm Development for Automated Irrigation

With a functioning data pipeline established, students began formalizing irrigation logic through computational models. Inputs included sensor readings and time-based constraints, while outputs controlled pumps and valves. Students encountered and addressed issues such as sampling frequency, response delay, and conflicting sensor signals. The physical implementation of the control system includes an Arduino microcontroller, relay module, and pump system, as shown in Figure 5.

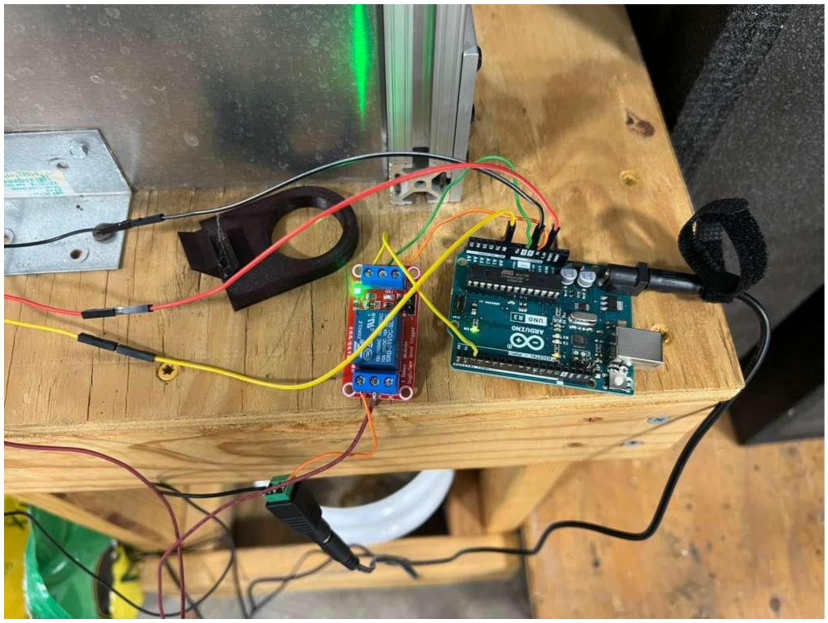

Figure 5. Arduino-based control system and pump integration

The integration of these components enables reliable actuation based on sensor input and programmed control logic.

Figure 6 illustrates an example of control logic implemented using the PASCO SPARKvue platform.

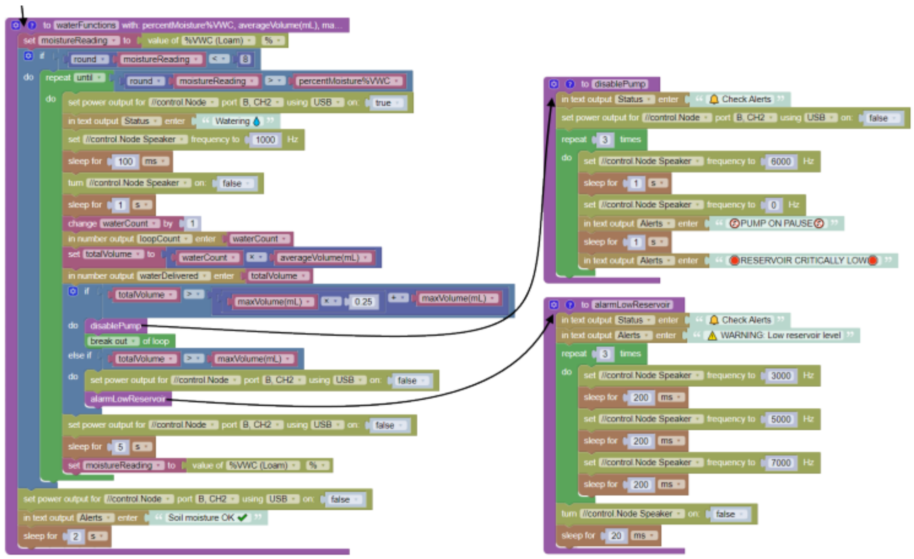

Figure 6. Sample PASCO / SPARKvue Control Code

However, this approach was later replaced with a more flexible Arduino-based system.

Rather than pursuing optimized performance, the emphasis was placed on model transparency and interpretability. The development of embedded control logic draws on established principles of electronic systems and sensor integration [9,12,14]. Algorithms were developed as educational tools to illustrate control theory concepts and system responsiveness. This approach ensured that programming reinforced conceptual understanding rather than functioning as a black box.

The implemented control strategy evolved into a hybrid threshold and time-delay algorithm. Initially, continuous threshold-based control caused excessive pump cycling and did not reflect real-world plant watering conditions. The final control logic operates as follows: when soil moisture exceeds a predefined dry threshold, the system activates a pump for a fixed duration. After watering, a mandatory delay period of approximately 48 hours is enforced before the next evaluation cycle. If soil moisture remains above threshold, the system enters a shorter delay loop (approximately 12 hours) until watering is required. This approach improved system stability by reducing rapid cycling and allowing natural processes such as drainage, evaporation, and plant uptake to occur.

An example implementation of the control logic in Arduino IDE is shown in Figure 7.

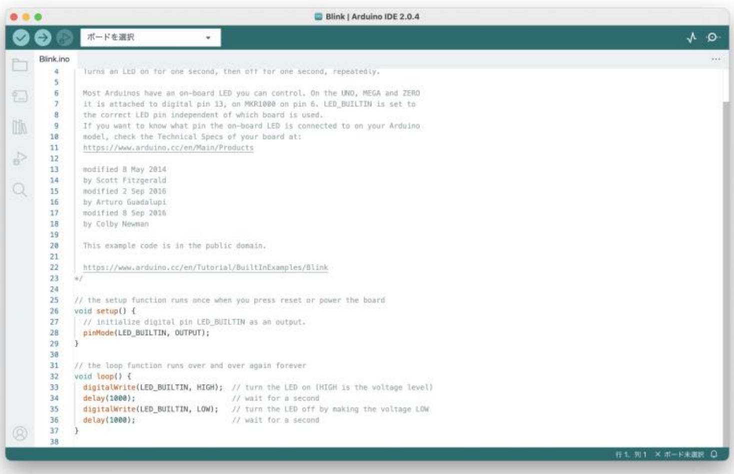

Figure 7. Example Arduino code implementing threshold and time-delay control

This implementation reflects the hybrid control strategy combining threshold-based triggering with time-delay logic.

The final implemented control strategy incorporates a hybrid threshold and time-delay approach. After each watering cycle, the system enforces a 48-hour delay before re-evaluating soil moisture. If moisture levels remain above the defined threshold, the system enters a shorter 12-hour delay loop until watering is required. This approach significantly reduced overwatering and improved overall system stability compared to continuous threshold-based control.

Sensor Fusion as a Next-Step Educational Challenge

Both the result described [3,6] identify sensor fusion as a logical next step. Students recognized that relying on a single variable, such as soil moisture, is insufficient for robust irrigation decisions. Environmental conditions such as temperature and humidity influence plant water needs and sensor interpretation.

The introduction of sensor fusion is framed not as an advanced research objective, but as an educational challenge [5]. Combining multiple sensor inputs encourages students to reason about system states holistically, reinforcing interdisciplinary and systems-level thinking.

Early Exploration of Data-Driven and AI-Based Approaches

As data collection matured, students began discussing the potential application of data-driven methods. While machine learning was not implemented during the semester, the accumulation of time-series data opened discussions about predictive irrigation, anomaly detection, and pattern recognition. Data-driven monitoring using sensor technologies has been shown to support early detection and decision-making in agricultural systems [5,12].

These discussions were intentionally exploratory. The goal was to expose students to the prerequisites and limitations of AI-based approaches, emphasizing data quality, context, and interpretability rather than algorithmic complexity.

System performance was evaluated based on: control stability (absence of unintended activations); repeatability across multiple cycles; response timing (approximately two-day drying cycle); reduction of oscillatory behavior. The time-delay control strategy significantly improved performance compared to continuous threshold-based control. These evaluation approaches are consistent with prior studies in sensor-based irrigation and environmental monitoring systems [11,13].

Experimental Validation Through Student-Designed Tests

Mechanical iteration remained a necessary component of automation. As described in [8] multiple bracket redesigns and water capture solutions developed to support sensor stability and reliable data acquisition. These iterations illustrate the interdependence of mechanical and digital subsystems.

Students learned that automation cannot compensate for physical instability or poor system design. Mechanical redesign thus became a supporting educational tool rather than the project's primary focus. The final system configuration installed in the Biological Sciences Center is shown in Figure 8.

Figure 8. PlantWall in Final Installed Configuration with integrated sensing and irrigation

This setup served as the testbed for evaluating system performance under real operating conditions. This configuration reflects the complete transition to a sensor-driven automated irrigation platform.

System validation was conducted through student-designed experiments rather than predefined benchmarks. Students established success criteria such as sustained sensor operation, consistent data logging, and stable control responses. Continuous operation over time served as a primary metric.

Hardware upgrades, including improved pump systems, are shown in Figure 9.

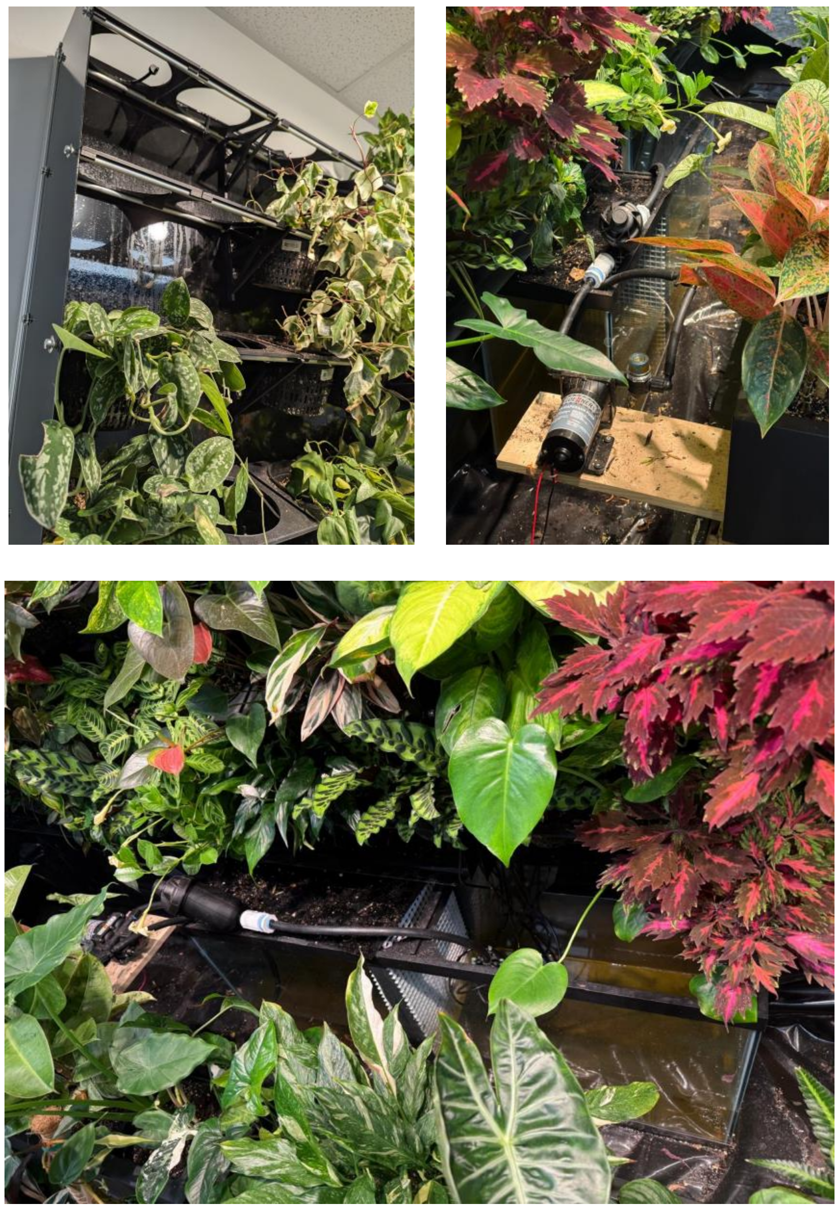

Figure 9. New Pump, Motor, and Supporting Hardware

These modifications addressed performance limitations identified in earlier system iterations.

This validation process reinforced experimental thinking and accountability. Students evaluated not only system performance but also the adequacy of their design assumptions.

Experimental results demonstrated that the system operated reliably under repeated cycles. Soil moisture sensors consistently distinguished between wet and dry conditions, triggering pump activation only when required. No unintended activations were observed during periods of sufficient moisture. A key observation was the non-uniform moisture distribution across the vertical system. Lower sections retained higher moisture levels due to gravitational accumulation, while upper sections experienced faster drying. This behavior highlights the limitations of top-fed irrigation systems and the need for distributed control strategies.

The observed moisture imbalance can be explained using fundamental fluid mechanics. Water movement in the vertical system is influenced by gravitational pressure $P = \rho g h$. This results in increased water accumulation in lower sections of the wall. Additionally, water delivery depends on pump flow rate and runtime: $V = Q \cdot t$. These relationships demonstrate the limitations of single-point irrigation control in vertically distributed systems.

Final system testing demonstrated stable and repeatable operation across multiple cycles. Soil moisture sensors consistently triggered irrigation only under dry conditions, and no unintended pump activations were observed. The system maintained reliable closed-loop behavior, confirming the effectiveness of the implemented control strategy.

The transition from the PASCO system to an Arduino-based solution was driven by practical limitations. The PASCO pump was unable to deliver water beyond approximately two feet, and the proprietary software limited flexibility in control logic. The Arduino-based system provided significantly greater adaptability, lower cost, and full control over irrigation algorithms, enabling more advanced experimentation and system optimization.

Experimental observations revealed a persistent non-uniform moisture distribution across the vertical system. Lower sections retained significantly higher moisture levels due to cumulative gravitational flow, while upper sections experienced faster drying rates. This phenomenon highlights a fundamental limitation of top-fed irrigation systems and reinforces the need for distributed or zoned irrigation strategies.

System testing confirmed: reliable detection of dry and wet soil conditions; consistent pump activation only when required; absence of unintended activations; stable operation across repeated cycles. These results validate the effectiveness of the implemented control system and confirm its suitability for automated irrigation applications.

Assessment of Student Learning Outcomes

Assessment was integrated throughout the semester. Progress reports functioned as formative assessments, documenting evolving goals, technical challenges, and reflective learning. The Semester Progress Report served as a summative evaluation of both technical achievements and conceptual growth. Vertical plant systems have also been used effectively to support student research and professional development [7].

Evidence of learning included improved technical vocabulary, increased autonomy in decision-making, and effective interdisciplinary communication. Students demonstrated a shift from task execution toward system-level reasoning.

Lessons Learned from an Automation-Focused Living Laboratory

Observations from weekly progress reports and instructor documentation indicate that students initially underestimated the complexity of data-driven control systems. Over time, students demonstrated improved ability to interpret sensor data, adjust control logic, and evaluate system-level behavior. These findings are based on documented observations and student reports rather than formal assessment instruments.

The living laboratory format allowed these lessons to emerge organically, providing deeper learning than short-term, isolated projects. Similar interdisciplinary botanical installations have demonstrated strong pedagogical value in engineering education [6].

Scalability, Transferability, and Future Intelligent Enhancements

The modular nature of the PlantWall supports scalability to other courses and institutions. Sensor-based experiments, control logic development, and interdisciplinary collaboration can be adapted to a wide range of educational contexts. Automated vertical botanical systems have also been explored in the context of sustainable agriculture and environmental design [10].

Future enhancements include wireless data transmission, cloud-based dashboards, and structured AI modules. These extensions will continue to prioritize educational value over system optimization. Modular automated botanical systems have been shown to support scalable and transferable educational implementations [8].

Conclusions: Educational Impact of Intelligent PlantWall Systems

The PlantWall project has evolved from a mechanical design challenge into an intelligent educational platform. The 2025–2026 phase demonstrates how automation, computation, and sensor integration can deepen student learning when embedded within a multi-year living laboratory.

The project’s greatest contribution lies not in technical novelty, but in its ability to cultivate systems thinking, interdisciplinary collaboration, and data-informed decision making. As such, the PlantWall serves as a transferable model for intelligent, experiential engineering education.

Bibliography

[1] Navitski, P., Budavich, R. L., Metellus, M. L., Lopez, D., & Ophus, J. V. (2025, June). Engineering Sustainable Solutions: The Plant Wall Project as an Interdisciplinary Approach to Integrating Design, Botanical Science, and Educational Innovation. In *2025 ASEE Annual Conference & Exposition*.

[2] Klehm, W. D., Navitski, P., & Swan, J. M. (2023). Board 182: Using of Esque Box for STEM Education of Pre-college Students (Work in Progress). Paper presented at the 2023 ASEE Annual Conference & Exposition, Baltimore, Maryland. URL: https://sftp.asee.org/42557

[3] Navitski, P., Moore, Q., Metellus, M., Lopez, D., & Ophus, J. (2025). Plant Wall: A multidisciplinary engineering design. *Proceedings of the VIII International Scientific and Practical Conference "Automotive Transport and Infrastructure"*, 214. Kyiv: National University of Life and Environmental Sciences of Ukraine.

[4] Navitski, P.M., Klachkov A. B. Sensors condition of plants for precision farming. International scientific and practical conference "The New Strategy of Scientific and Educational Priorities in the Context of Agrarian- Industrial Development" (Almaty, 27-29 November 2015). – Kazakhstan, Almaty: KazNAU, 2015 – p. 264-269.

[5] Navitski P., Ruckelshausen A. Ecological monitoring of pesticide drift of machines for chemical plant protection in the republic of Belarus using sensors technologies. Proceedings of the V International conference: "Digital Education at Environmental Universities", 17-18 October 2018, National University of Life and Environmental Sciences of Ukraine, Kyiv, Ukraine, 2018. – pp. 118-121

[6] Pavel Navistki, Tanner Craig, Anna Kinnunen, Nate Youmans, Hannah Marie Lucy, Rachel Budavich, William Ranahan, Stuart Resor, The Thurman Botanical Tapestry: Integrating Botanical Aesthetics, Scientific Innovation, and Pedagogical Enrichment. 2024 ASEE Annual Conference and Exposition in Portland, Oregon.

[7] T Craig, A Kinnunen, G Lucy, N Youmans, P Navitski. The Innovative Vertical Plant Garden: Integrating Engineering Design and Botanical Research for Research and Student Development. 42nd Annual Oklahoma AIAA - ASME Symposium, April 13, 2024, School of Engineering, Oral Roberts University, Tulsa, Oklahoma, USA p. 26.

[8] Pavel Navistki, Garrison Lucy, Tanner Craig, Anna Kinnunen, Nate Youmans, Hannah Marie Lucy, Rachel Budavich, William Ranahan and Stuart Resor. Innovative Design of an Automated, Modular Vertical Botanical Display with Integration of Architecture and Engineering. E3S Web Conf., 497 (2024) 02017. DOI: https://doi.org/10.1051/e3sconf/202449702017.

[9] Клочков, А. В., Новицкий, П. М., Ковалев, В. Г., & Гусаров, В. В. Электронные системы и устройства сельскохозяйственных машин. Учебное пособие для студентов учреждений высшего образования по специальности "Техническое обеспечение процессов сельскохозяйственного производства" / Минск, 2019.

[10] Pavel Navistki, Garrison Lucy, Tanner Craig, Anna Kinnunen, Nate Youmans, Hannah Marie Lucy, Rachel Budavich, William Ranahan, Stuart Resor, Victar Taustyka, Automated modular botanical tapestry designed to integrate various plants into a flat vertical structure. 29th International Scientific Conference Challenges to Sustainable Agriculture, Protection of Rural Areas, Water Resources and Environment Date and venue of the Conference September 26-28, 2023. Institute of Technology and Life Sciences - National Research Institute al. Hrabska 3, Falenty, Poland.

[11] Pramanik, M. (2022).
Automation of soil moisture sensor-based basin irrigation system.
Agricultural Technology, 2, Article 100032.

[12] Parthiban, S., Nithishkumar, A., & Bharathraj, R. (2025).
Design and implementation of a smart irrigation system using Arduino and IoT.
International Journal of Scientific Research and Engineering Development, 8(5), 1–6.

[13] Gradiz, A., & Dong, Y. (2025).
Utilizing soil moisture sensors for efficient irrigation management.
Michigan State University Extension.

[14] Arduino Documentation.
Arduino Uno Rev3 – Technical Specifications.
https://docs.arduino.cc