WIP - Design of Experiments for Monitored Sustainable Wireless Farming

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Abstract

This Work-In-Progress Abstract describes a Design, Build and Test (DB&T) exercise that began within the Senior Capstone Course in the Electrical & Computer Engineering (ECE) curriculum, where student Teams carry out exercises designed to train them in research and research methods. It serves as the centerpiece and professional development component of the ECE curriculum and aligns well with ABET assessment guidelines and outcomes. Without exception, all projects are successive team efforts with applications. Teams consist of between three (3) and five (5) members, the selection of a project topic and the choice of a Team-Lead. It describes work carried out by undergraduates on Wireless Sensor Networks (WSNs) and on instrumentation technologies for the Internet of Things (IoT) that integrate seamlessly with state-of-the-art applications. These offer real-time, automated data collection, enabling precision and improved efficiency and sustainability. These technologies offer scalable solutions across a range of applications in monitoring and automation. The outcomes and student feedback show how this project on system monitoring, control fundamentals, and analysis impacted their engagement and success. Based on current studies and market needs, WSN and IoT technologies address critical challenges in agriculture, including labor efficiency, water conservation, and crop health monitoring and management. It also positions them as essential instrumentation and tools for sustainable gardening and farming. The purpose is for a team of undergraduate students to design, build, and test a sustainable food-production ecosystem that can be monitored. This paper also emphasizes the need for Engineering educators to prepare students for an increasingly multidisciplinary world that is evolving in real time because it would offer the students opportunities to fit into industries as they adjust towards sustainable innovation and high-quality product development and instrumentation.

Introduction

Agriculture is the foundation of any thriving society, yet it must adapt to technological advancements to meet modern demands. Wireless Sensor Networks (WSNs) and the Internet of Things (IoT) are two cutting-edge technologies that integrate seamlessly with agriculture. Designed to enable real-time data collection and precision farming for improved efficiency and sustainability, these technologies offer scalable solutions across applications, from soil monitoring to automated irrigation. Based on current research and market needs, WSN and IoT technologies address critical challenges in agriculture, including labor efficiency, water conservation, and crop health management, positioning them as essential tools for sustainable gardening and farming

The effort reported here is a capstone project in the Electrical and Computer Engineering Department in the State University. The course design requires a team of three to five students to demonstrate their ability to design a working system of sufficient complexity, starting from a single-sentence objective using engineering principles, teamwork, and leadership. The learning objectives for the course are:

1. Demonstrate an ability to apply knowledge of mathematics, science, and engineering
2. Demonstrate an ability to design, simulate, build and conduct experiments, as well as to analyze, and interpret data
3. Demonstrate an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, manufacturability and sustainability
4. Demonstrate an ability to use modern engineering hardware and software tools
5. Demonstrate an ability to function on multi-disciplinary teams
6. Demonstrate an understanding of professional and ethical responsibility
7. Demonstrate an ability to communicate effectively, write technical documents and give oral presentations related to design project results
8. Demonstrate an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice

The students are evaluated on how well they identify engineering challenges through a comprehensive literature review, find the technical information that supports the project's goals and objectives, and apply what they have learned to the project at hand. Communication skills are evaluated by expecting a requirement's documentation, a preliminary design review document and oral presentation, and a final report, presentation, and demonstration in an engineering-wide extravaganza that is open to the public. Each team selects one member as the team lead. Every team member has documented assigned tasks, schedules, and entrance and exit criteria for each, which are reported in the regular class sessions.

This paper focuses on the associated instrumentation and implementation of a 'progressive' design, build, and test exercise for a sustainable ecosystem monitored by electronic control systems. Key sustainable solutions in the future of this design effort will include solar-powered systems and energy-efficient irrigation to address energy and water management challenges. Wireless low-power communication via LoRa devices will enable remote monitoring of environmental parameters to support effective data collection, transmission, and system control. Additionally, planned sensor selection will provide control over irrigation to optimize plant growth. This project draws on concepts like proximity sensors, circuit design, and embedded systems as part of a Capstone Project involving Senior Electrical & Computer Engineering undergraduates.

The project incorporates essential components to monitor a biosystem such as temperature, moisture, water level, light, pH, and toxic compounds. The most expensive parts will likely be the hardware. Basic parts of an agricultural/aquaponics system, like the tank, filters, plant substrate, pump, and plumbing, are expected to be commonly available.

Review of Literature

The first task in the design process is to search the literature for recent and relevant publications on the project topic, in this case, wireless monitoring and assisted farming. Students learn what has been done and how others have solved similar design challenges. Students practice research and learn to find relevant information from scholarly research. Traditional methods and benefits of greenhouse gardening, as well as the different climate-control techniques to improve plant health, are discussed in [1,2], and the benefits of using solar energy are outlined in [3]. The biological and technological aspects of aquaponics and related systems are described in [4, 5, 6]. Costs and sustainability are addressed in [7,8], demonstrating how costs can be minimized while environmental benefits are achieved. The ideal is to grow and harvest as much nutritional content as possible while minimizing negative ecological impact. This often calls for solar power, as seen in greenhouses, and the addition of fish as a protein source, as shown in Figure 1.

Sustaining a complex ecosystem involves attention to microorganisms and automation [9,10]. The conditions are critical for fish farming in aquaponic systems [11,12, 13]. Figure 2 shows one possible implementation of an aquaponic system that grows plants in rafts and raises fish in a separate tank.

Figure 1: Species of Fish & corresponding Tank size [12]

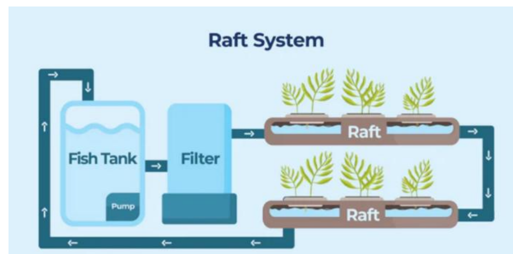

Figure 2: Raft Aquaponics System [13]

Automation plays a crucial role in sustainable farming [14,15]. Automation implies control systems, which have been a topic of great concern for maintaining water quality, light, water level, and circulation [16,17,18,19], and one report describes a data-driven control system using machine learning [20].

Embedded systems are key components of most systems in the literature. Microcontrollers are used as computer engines in monitoring, controlling, and reporting systems [21-25]. For decades, aquaponics has emerged as a growing application of the Internet of Things (IoT) for remote monitoring and cloud storage [26, 27, 28]. IoT sensors and systems have enabled distributed sensing and computing in agriculture and aquaculture [29,30], especially LoRa technology, which enables wide-area wireless networks with low-cost nodes that monitor moisture, light, and temperature [31, 32, 33]. Field Programable Gate Arrays (FPGA) and distributed computing have been used to augment small and large-scale agriculture as well [34, 35].

Sensors are essential for maintaining the health of the growing system. Controlling pH is crucial in sustaining an aquaponic system containing plants and animals in a semi-closed system [36]. Water and air temperature sensing and control are the final considerations for maintaining healthy growth [37,38,39].

Once students have established the knowledgebase, they can make informed design choices and decisions about how to meet project goals and objectives. The next logical step is to create a set of requirements and verification methods, based in part on the literature and the project's goals. These include water condition, remote monitoring, Size, Weight, and Power (SWaP).

Peer review is an important step at this stage. A mid-semester review and presentation is a chance to glean insight into what was omitted or not thought through. This is part of the Design-Refine-Design process. The following sections describe the Build and Test phase of each project.

Description of the Approach

The agriculture/aquaponics monitoring system was designed using a centralized control structure based on the Raspberry Pi 3B+, which served as the main processing unit for data acquisition and future wireless transmission. The initial concept involved deploying several environmental sensors specifically for temperature, water level, pH, toxic compounds, light intensity, and soil moisture throughout the ecosystem to track critical metrics in real time. However, due to hardware delays and integration problems, only the water temperature sensor was fully implemented in the prototype phase.

Figure 3 shows a draft sketch of the student-designed system. Key sustainable components in this design include solar-powered systems and energy-efficient irrigation aimed at addressing energy and water management challenges. This WIP project introduces the design and implementation of smart monitoring and control systems using a Raspberry Pi 3B+ as the main processing unit. A sensor network will monitor critical environmental conditions. The Raspberry Pi processes this data, displays it on an LCD screen, and activates components like the water pump based on real-time monitoring using an algorithm partially shown in Figure 4. Data is also logged for future analysis and can be accessed wirelessly for remote monitoring and processing. Additionally, various other sensors will provide control over irrigation to optimize plant growth. This project offers a long-term data acquisition intention that draws on concepts like proximity sensors, circuit design, and embedded systems, and it incorporates essential components to monitor a biosystem such as temperature, moisture, water level, light, pH, and toxic compound. For sustainability, the system can be alternatively powered by a rechargeable lithium battery, a voltage regulator, and an on-board solar panel. The goal is to create a system with the potential for integrating renewable energy (Fig.7), IoT, and automation in a sustainable food production scheme.

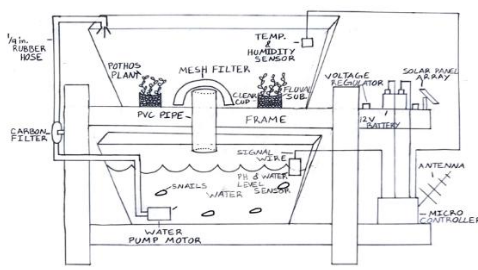

Figure 3. Initial Design

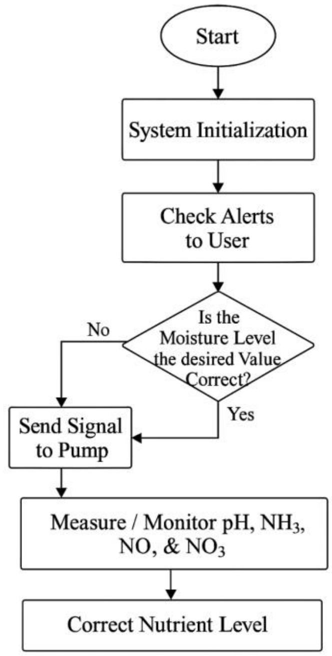

Figure 4. Flow chart for Main Driver Program (MDP)

The operational approach focused on establishing functional connectivity between the waterproof digital temperature sensor and the Raspberry Pi. This sensor was selected for its compatibility with Raspberry Pi's GPIO (General Purpose Input Output) interface, reliability in aquatic environments, and built-in digital output, which reduced the need for external signal conditioning circuitry. Python-based scripts were written to initialize the sensor, read raw data, and convert binary outputs into temperature values in Celsius. These readings were printed onto a local display and stored internally for verification.

Although solar power was a critical component (see Figure 7 below) of the original design, it was excluded from the working prototype due to unresolved power regulation issues and insufficient voltage stability during testing. Consequently, the system was powered via a direct wired 5V DC supply to ensure uninterrupted operation of the temperature monitoring module. This adaptation allowed testing of the primary sensing connectivity and functionality without introducing power-related variables.

The focus was strictly on establishing baseline functionality through physical integration, software communication, and repeatable measurement cycles that can be sustained. Planned power consumption, efficiency, and sensor calibration calculations were postponed until a fully integrated version of the system can be deployed.

Experimental Results & Discussions

Experimental testing was limited to the water temperature sensor subsystem, as this was the only operational component successfully integrated into the prototype. The DS18B20 temperature sensor was submerged in a small test tank containing clean water to simulate conditions of an agriculture/aquaponics system. Temperature readings were recorded over several intervals across multiple days to evaluate measurement consistency, sensor reliability, and stability of system output.

Temperature data displayed reliable performance with readings that varied only slightly between sessions, typically within a 1°C range. The readings reflected ambient conditions and followed expected trends over time, confirming basic sensor accuracy and data transmission integrity. No errors were observed during polling cycles, and the connection between the Raspberry Pi and the sensor remained stable and repeatable throughout all test sessions.

The results confirmed successful hardware integration and interfacing, correct software implementation, and stable data acquisition under basic conditions. All temperature readings were verified by comparing values to those obtained from a standard household digital thermometer placed alongside the sensor in the water. While these measurements were not formally calibrated or graphed, the visual correlation between both sources was consistent and acceptable for this proof-of-concept stage.

The testing also identified some limitations that will be addressed in future iterations. Without an active filtration or aquatic life system in place, temperature fluctuations were limited, reducing the opportunity to observe dynamic system responses. Additionally, without the full implementation of a Solar power hardware and with the other sensors offline, the full system functionality as a wireless environmental monitor could not be assessed. Nevertheless, the successful operation of the temperature sensing module serves as a foundational step toward full sensor deployment and closed-loop environmental control in future development cycles.

Fig 5: Design Front View

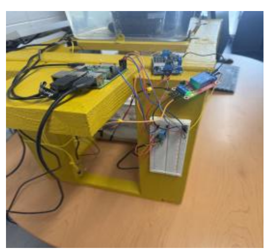

Fig 6: Design Side View

Fig 7: Design with Solar Panel

Figure 8: Aquaponics Monitoring System on the Raspberry Pi

Conclusions

The articles cited in the narrative demonstrate how technology can improve the effectiveness and manageability of aquaponics and agricultural systems. The plants and fish are kept healthy by using sensors, Internet of Things devices, and automated control systems to monitor critical parameters like temperature, nutrient levels, and water quality. Other technologies that improve food production while using less energy and water include biofiltration, greenhouse farming, and renewable energy. These technologies enable the development of more self-sufficient and sustainable farming systems, despite certain obstacles such as increased setup costs and system complexity. The future of the project will be guided by this study to create an intelligent aquaponics/agriculture control system.

The observations demonstrate an operational proof of concept for aquaponics monitoring and control. The project required investigation of combining aquaculture techniques, circuit design, solar power, battery management, sensor data protocols, and embedded systems. The device will continue to operate through the Fall 2025 and Spring 2026 semesters to collect long-term data.

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