Bio-Automated System with Intelligent Lighting Hydroponics for Enhanced Rapid Bloom (B.A.S.I.L. H.E.R.B.)

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Abstract — This paper presents the design and implementation of a smart hydroponic system for automated herb cultivation. The system integrates advanced sensing, lighting control, and web-based monitoring to create optimal growing conditions. Key features include real-time environmental monitoring, automated nutrient delivery, and intelligent LED lighting control. The system utilizes color sensing to detect plant health issues and implements advanced deficiency detection mechanisms for enhanced growth stimulation. Testing demonstrates the system's capability to maintain stable growing conditions while providing users with remote monitoring and control capabilities.

Index Terms — Environmental Monitoring, Hydroponics, LED Control, Smart Agriculture, Web-Based Control

I. INTRODUCTION

Demand for locally-grown organic produce is rising, with sales reaching $50.1 billion in 2019. Traditional gardening poses challenges, especially for those with limited time or expertise—31% of adults struggle to maintain a healthy diet due to time constraints. The B.A.S.I.L. H.E.R.B. system (Bio-Automated System with Intelligent Lighting Hydroponics for Enhanced Rapid Bloom) offers an automated indoor solution for herb cultivation. This system combines a Deep Water Culture hydroponic setup with sensors for temperature, humidity, pH, and light intensity, using LED lighting to optimize photosynthesis. An ESP32 microcontroller adjusts growing conditions based on real-time data, while a color sensor tracks leaf health. Accessible via a web-based interface, the system allows remote monitoring and control through any internet-connected device. It's deployed on DigitalOcean with an AWS Lightsail database, integrating OpenAI's API for intelligent plant care suggestions. This streamlined solution enables year-round, low-effort herb cultivation for busy individuals.

II. SAFETY REQUIREMENTS

The B.A.S.I.L. H.E.R.B. system adheres to multiple safety standards to ensure user protection and electrical safety compliance. The core electrical design follows UL 1951 (Standard for Electric Plumbing Accessories), which governs safety requirements for electrical equipment in contact with water. Additionally, the system complies with IEC 60335-1 for household electrical appliances safety, focusing particularly on protection against water ingress (achieving IPX4 rating for splash resistance) and electrical isolation between high and low voltage circuits. For electromagnetic compatibility, the system follows FCC Part 15 Class B requirements, ensuring minimal interference with other electronic devices in residential environments.

To guarantee operational safety, the system implements multiple protection mechanisms. These include over-temperature protection (OTP) that triggers at 85°C, short circuit protection (SCP) with a 2μs response time, and water level monitoring that automatically disables the pump if water levels fall below critical thresholds. The LED system is current-limited and thermally monitored to prevent overheating. The following table summarizes the key safety parameters and their corresponding standards:

Safety Parameter	Requirement	Standard
Operating Voltage	120V AC, 60Hz	UL 1951

Water Protection	IPX4 Rating	IEC 60335-1
Temperature Limit	85°C max	Internal Spec
EMI/EMC	Class B Limits	FCC Part 15
Short Circuit Response	< 2µs	Internal Spec
Ground Fault Protection	5mA trip current	UL 943
Isolation	3000V AC	IEC 60335-1

Table 1

III. SYSTEM ARCHITECTURE

A. Hardware Components

The B.A.S.I.L. H.E.R.B. system integrates several hardware components to maintain optimal growing conditions for basil plants, controlled by an ESP32-WROOM-32 microcontroller. Key components include:

Sensing Unit:

TCS34725 Color Sensor: Detects leaf color variations to identify potential nutrient deficiencies.

DHT11 Temperature and Humidity Sensor: Measures ambient temperature and humidity.

OPT3001 Ambient Light Sensor: Provides real-time data on light intensity.

pH Sensor: Monitors the nutrient solution's acidity, essential for nutrient absorption.

Control Unit:

ESP32-WROOM-32 Microcontroller: Acts as the central processing unit, managing sensor data, adjusting lighting, and controlling the water pump based on environmental readings.

Custom PCB: Houses and connects all sensors, actuators, and power regulation circuits, ensuring efficient data communication across components.

Lighting System:

WS2812B RGB LED Array: Provides specific wavelengths for photosynthesis, customizable to basil growth stages (seedling, vegetative, mature).

Lighting Control: Adjusts intensity and spectrum based on sensor input, simulating natural daylight cycles.

Hydroponic System:

Deep Water Culture (DWC) Configuration: Allows roots to be submerged in nutrient-rich water.

Automated Nutrient Delivery: Regulates nutrient solution through a pump, ensuring a steady supply.

Circulation Pump: Ensures water movement, preventing stagnation and promoting oxygen flow.

B. Software Architecture

The software architecture is structured in three layers to handle data acquisition, processing, and user interaction:

Microcontroller Layer: Manages data collection from sensors and sends control signals to adjust LEDs and pump activity. This layer operates in real-time, with data processed every few seconds to maintain a responsive system.

Cloud Backend:

Hosted on Digital Ocean, the backend server runs on an Express.js framework, connecting the ESP32 to a MySQL database which is stored on AWS. Our system integrates with OpenAI's API for advanced analysis of environmental data, providing plant care insights based on sensor readings

Web Interface:

Built using Angular, this front end offers a real-time monitoring dashboard where users can view environmental data, control the lighting schedule, and monitor plant health status.

IV. PCB DESIGN AND IMPLEMENTATION

A. PCB Design Process

The PCB design process for the B.A.S.I.L. H.E.R.B. system was pivotal in creating an efficient and integrated platform to house and connect all essential components. Using KiCAD, an open-source PCB design software, the team created schematic and layout drawings, generating gerber files for manufacturing. This process involved custom configurations, symbol libraries, and footprint libraries to ensure that each component was accurately represented and positioned. KiCAD's functionality allowed for seamless integration of third-party parts, as well as custom symbol creation for specific components).

B. Component Placement and Circuit Design

The primary goal in the PCB layout was to optimize the spatial arrangement of the core components, including the ESP32 microcontroller, relays for motor control, voltage regulators, and sensor interfaces. The design was organized to maintain short, direct trace paths between components, minimizing signal interference and promoting stable connections.

Key components included:

Microcontroller: The ESP32-WROOM-32, serving as the system's central processing unit, was placed at the PCB's core to enable efficient connections to peripheral sensors and actuators.

Voltage Regulators: Three regulators (5V, 3.3V, and 1.8V) were strategically located to supply different voltage levels to various components, enhancing stability across the circuit.

Sensor Interfaces: Dedicated headers for sensors such as the DHT11 (temperature/humidity), TCS34725 (color), and OPT3001 (light intensity) facilitated modular assembly and testing of sensor configurations.

C. Trace Routing and Layer Management

After the initial layout, the team transitioned from the schematic to PCB layout, focusing on trace routing and layer management. Due to the complexity of signal routing, especially with mixed high- and low-voltage traces, vias were used to connect different PCB layers. This enabled efficient signal distribution without congestion in the layout.

For this design, the board utilized a two-layer structure:

Top Layer: Primarily for component placement and power connections.

Bottom Layer: Reserved for the ground plane, ensuring robust grounding across the board.

By implementing a ground plane, the PCB achieved better signal integrity, reduced noise, and enhanced the stability of the entire system. Special attention was given to routing paths for high-frequency components to mitigate electromagnetic interference.

D. PCB Fabrication Standards and Testing

To ensure the board's reliability, the design adhered to the IPC-2221 standards for PCB fabrication. This globally recognized standard provides guidelines on electrical, thermal, and mechanical design considerations. Adopting IPC-2221 ensured that the PCB design was reliable, manufacturable, and met the required performance standards for hydroponic applications(Group 5_ 120 Page Report).

The board was prototyped and tested through various stages, including continuity checks, short circuit tests, and component testing. Each component was tested individually for functionality, and then the board was tested as a complete system to verify stability under operating conditions. Figures 1 and 2 illustrate the completed PCB with fully populated components, showcasing the transition from digital design to a functional prototype.

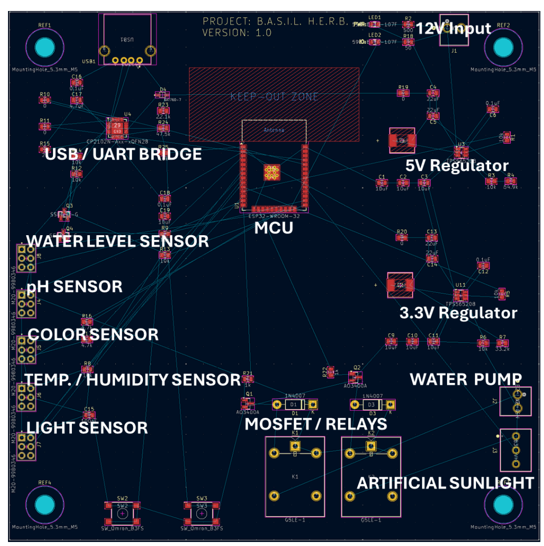

Fig. 1 PCB Schematic

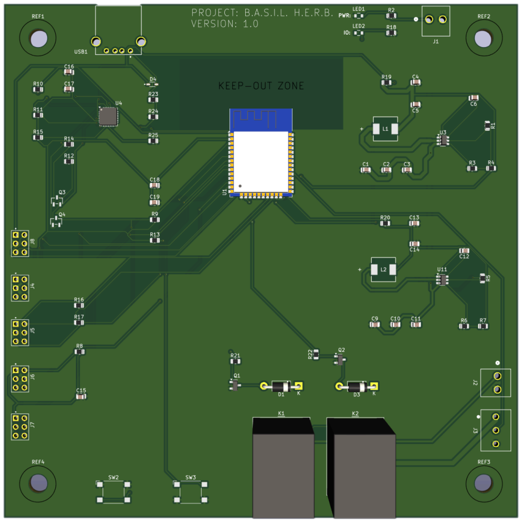

Fig. 2 Breakout Board CAD Model

E. Assembly and Integration into the System

The completed PCB was integrated into the B.A.S.I.L. H.E.R.B. system, connecting seamlessly with the sensors, lighting, and hydroponic components. Each sensor interface was tested for data accuracy, confirming that readings were correctly relayed to the microcontroller for processing. Additionally, the relay circuits for the water pump and nutrient delivery system were tested to ensure safe and responsive operation.

The final PCB assembly demonstrated reliable operation under testing conditions, with stable power distribution and efficient data communication across components. The design's compact layout contributed to its ease of integration within the hydroponic enclosure, optimizing space and maintaining accessibility for potential future adjustments.

V. ENVIRONMENTAL CONTROL SYSTEM

The environmental control system forms the core of B.A.S.I.L. H.E.R.B.'s ability to maintain optimal growing conditions. Through extensive research of basil cultivation requirements, we identified critical environmental parameters that directly impact plant health and growth rate. The system actively monitors and controls temperature, humidity, pH levels, and light intensity through an integrated network of sensors coordinated by the ESP32-WROOM-32 microcontroller. Each sensor was selected based on accuracy requirements, response time, and cost-effectiveness, as detailed in Table 2.

Sensor Type	**Model**	**Range**	**Accuracy**	**Response Time**
Temperature	DHT11	0-50°C	±2°C	<6 seconds
Humidity	DHT11	20-80%	±5% RH	<6 seconds
pH	SEN0161	0-14 pH	±0.1 pH	<30 seconds
Light	OPT3001	0-100K lux	±5% FSR	<1 second
Color	TCS34725	RGB + Clear	±5% FSR	<1 second

Table 2

The lighting system utilizes WS2812B RGB LED arrays, carefully configured to emit specific wavelengths essential for photosynthesis and plant development. This setup enables the system to provide tailored light spectra that cater to the unique needs of plants at various stages of growth. Through precise programmatic control, the system maintains these optimal light conditions, adjusting dynamically as plants progress from one phase to the next. Operating on a customizable schedule, the LED system simulates natural daylight cycles, delivering both the intensity and spectral distribution outlined in Table 3, thus promoting healthier and more efficient plant growth.

Growth Stage	**Blue Light (450-480nm)**	**Red Light (620-750nm)**	**Daily Duration**
Seedling	30%	70%	14 hours
Vegetative	40%	60%	16 hours

Mature	35%	65%	14 hours

Table 3

The hydroponic system operates using a Deep Water Culture (DWC) configuration, in which plant roots are suspended directly in a nutrient-rich water solution to facilitate easy nutrient absorption. To ensure that plants receive a consistent supply of oxygen and nutrients, a submersible pump running at 1 liter per minute maintains optimal water circulation. This flow is critical for promoting root health and preventing stagnation, while the pH monitoring system continuously samples the nutrient solution, allowing for early detection and correction of any pH imbalances that could hinder nutrient uptake. Temperature regulation is managed through ambient air control, with the system carefully maintaining a range of 21-29°C to support ideal growth conditions. The integrated color sensor plays an essential role in monitoring plant health by assessing leaf color as an indicator of nutrient status. Utilizing the TCS34725 sensor, RGB values of leaf color are analyzed and compared to known profiles of healthy basil leaves, enabling early identification of potential nutrient deficiencies. Table 4 presents a detailed outline of color indicators used to detect specific nutrient deficiencies, aiding in proactive management of plant health.

Condition	R Value	G Value	B Value	Indication
Healthy	80-120	140-180	60-90	Normal
N Deficient	140-180	140-160	40-60	Yellowing
P Deficient	120-140	100-120	100-140	Purpling
K Deficient	160-200	120-140	40-60	Browning

Table 4

VI. DATA PROCESSING AND CONTROL

A. Color Analysis for Nutrient Deficiency Detection

The B.A.S.I.L. H.E.R.B. system's data processing capabilities leverage color analysis to detect and address nutrient deficiencies in real time. Utilizing a TCS34725 RGB color sensor, the system continuously monitors the leaf coloration, which acts as a proxy for plant health. Leaf color deviations—specifically in red, green, and blue values—correlate with specific nutrient deficiencies.

To enhance accuracy, the system incorporates spectral analysis with a formula calculating sensor sensitivity at specific wavelengths:

$$S(\lambda) = \frac{P(\lambda)}{E(\lambda)}$$

where

S(λ) is the sensor's sensitivity at wavelength

P(λ) is the detected power of light, and

E(λ) is the irradiance. The TCS34725 sensor's response to each wavelength allows the system to identify common deficiencies:

Nitrogen (N) Deficiency: Identified by leaf yellowing, particularly a decrease in the green spectrum values.

Phosphorus (P) Deficiency: Detected as purpling in leaf tissues, indicated by an increase in the red spectrum values.

Potassium (K) Deficiency: Noted through browning edges, detectable by decreases in blue spectrum values.

This continuous monitoring allows for real-time adjustments to nutrient levels in the hydroponic solution, ensuring optimal growth conditions and preventing prolonged deficiency.

B. Data Acquisition and Environmental Control Loop

The ESP32-WROOM-32 microcontroller serves as the primary processing hub, orchestrating data acquisition and environmental control based on sensor input. The microcontroller communicates with Digital Ocean to log data in real-time, ensuring all sensor readings are available for analysis and historical review via the web interface.

Each sensor transmits data to the microcontroller, which then processes it according to predefined thresholds. For example:

Temperature and Humidity: Data from the DHT11 sensor prompts activation of heating or cooling mechanisms if readings fall outside the optimal range for basil growth (21-29°C, 40-60% humidity).

pH Levels: Readings from the SEN0161 pH sensor enable dynamic adjustments to nutrient solution acidity, helping maintain a stable environment conducive to nutrient uptake.

Light Intensity: The OPT3001 ambient light sensor and WS2812B RGB LEDs provide adaptive lighting, simulating natural daylight cycles with adjustable blue and red wavelengths (as shown in Table 3), optimized for basil at each growth stage.

The processing loop for environmental adjustments operates with a response time under 5000ms for each control action, allowing the system to swiftly adjust environmental conditions.

C. Data Storage and Cloud Integration

The B.A.S.I.L. H.E.R.B. system stores data in a MySQL database on AWS Lightsail, logging sensor data, user inputs, and system adjustments for traceability and analysis. The schema is optimized with indexes for high-frequency data logging. Security is ensured through backend input validation, allowing only authenticated commands and preserving cultivation process integrity.

D. System Workflow and Control Diagram

The system workflow, depicted in Figure 3, demonstrates the data flow from sensor input through processing to actuation. The workflow begins with sensor data collection, which is relayed to the microcontroller. Based on programmed thresholds, the microcontroller issues commands to adjust the environment as needed.

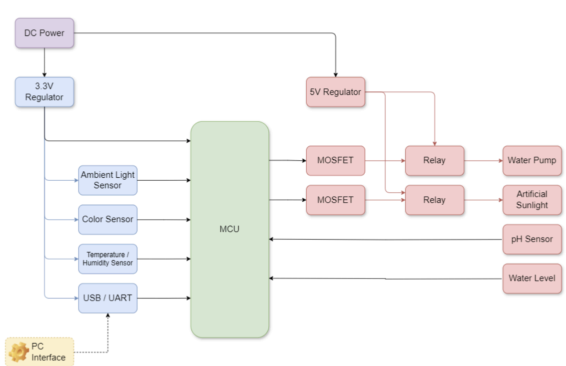

Fig. 3 MCU Workflow

This streamlined data processing and control loop forms the backbone of the B.A.S.I.L. H.E.R.B. system, ensuring that plants receive optimal conditions without continuous human intervention.

VII. WEB APPLICATION AND MONITORING

A. Cloud Infrastructure and Database Management

The B.A.S.I.L. H.E.R.B. system utilizes Digital Ocean for its cloud deployment, providing a robust and scalable infrastructure that facilitates real-time data processing and remote monitoring. A MySQL database instance on AWS stores critical data such as sensor readings, system thresholds, and user preferences. The choice of MySQL, a relational database, ensures efficient querying and data integrity, supporting high-frequency data logs essential for responsive system performance.

This setup is optimized for lightweight operations, allowing the MCU to seamlessly transmit data to and from the database. The system uses minimal triggers or stored procedures to reduce complexity, focusing instead on a streamlined data pipeline for rapid data retrieval and control feedback. This structure minimizes latency in data transfers and ensures users can monitor and adjust plant parameters efficiently.

B. Real-Time Monitoring and Control

The user interface of the B.A.S.I.L. H.E.R.B. system offers a comprehensive, real-time dashboard for monitoring plant health metrics and system status. Built with AngularJS, the frontend provides a single-page application experience, enabling smooth and instantaneous data updates without the need for page reloads. This interface is structured around the following features:

Sensor Data Display: Real-time updates on parameters such as temperature, humidity, light intensity, and pH levels. These metrics are visualized using dynamic graphs, allowing users to quickly assess the growing environment's status.

Historical Data Access: Users can view historical data trends to make informed decisions regarding nutrient or lighting adjustments. By tracking growth patterns, users gain insights into how environmental changes affect plant health over time.

The system also includes alert notifications to inform users of critical conditions, such as water level drops or extreme temperature fluctuations. Alerts are configurable via the user interface, with options for email and SMS notifications, ensuring prompt action can be taken regardless of the user's location.

C. Remote Adjustment and AI-Driven Recommendations

The B.A.S.I.L. H.E.R.B. system enables users to actively manage plant environments via a web interface. Key features include:

Lighting and Water Pump Control: Users can adjust LED spectrum and water schedules, with recommendations based on real-time sensor data.

AI-Powered Plant Health Analysis: Using OpenAI's API, the system analyzes sensor data to suggest care adjustments, acting as a virtual plant care assistant.

Machine learning further personalizes recommendations based on each plant's conditions, enhancing adaptability and user experience.

D. Data Security and User Authentication

The application uses secure HTTP endpoints with JSON Web Token (JWT) authentication, allowing only verified user access. Sensitive data, like credentials, is encrypted, and an auto-logout after 20 minutes of inactivity enhances security. Regular cloud backups ensure data resiliency and availability.

E. Workflow and System Integration

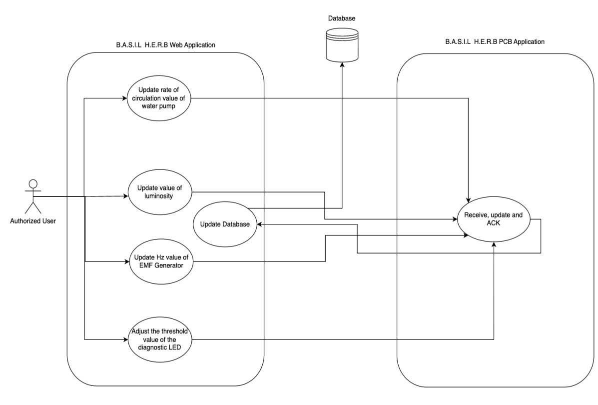

Figure 4 Case Diagram

The web application's workflow, illustrated in Figure 4, demonstrates the process of receiving, processing, and responding to user commands. When a user sends a command—such as adjusting the LED lighting frequency—the request is processed by the Node.js backend, which constructs an HTTP POST request to the ESP32 MCU. The MCU then executes the command and returns a confirmation to the server, which updates the dashboard to inform the user of successful execution.

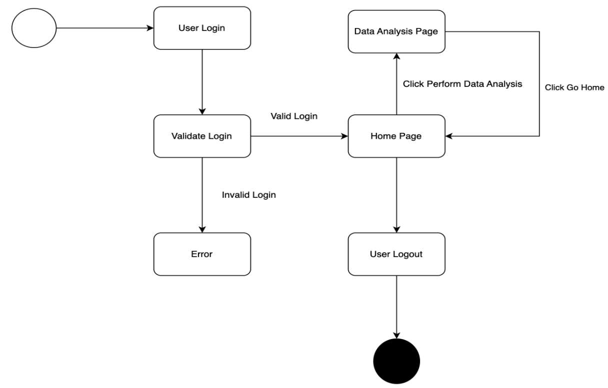

Figure 5 User Interface Schematic

VIII. EXPERIMENTAL RESULTS

A. Sensor Testing and Validation

Each sensor underwent functionality testing:

DHT11 Temperature/Humidity Sensor: Accurately detected environmental changes with updates in under 6 seconds.

OPT3001 Ambient Light Sensor: Showed high sensitivity to light intensity changes, effectively controlling LED brightness.

TCS34725 Color Sensor: Accurately identified RGB values, supporting early detection of nutrient deficiencies like nitrogen and potassium.

B. LED Lighting and Environmental Control

The WS2812B RGB LED array demonstrated responsive, stage-specific lighting adjustments. It maintained a blue-red light ratio of 40%-60% for vegetative growth over a 16-hour cycle, with real-time updates in response to changes detected by the light sensor.

C. Water Pump and Hydroponic Circulation

Testing confirmed consistent flow at 1 liter per minute in the hydroponic setup, supporting nutrient distribution and root health. The pump's responsiveness allowed flow adjustments for different growth stages, ensuring a stable environment within the DWC system.

D. System Response Time and User Interface

Response times were satisfactory:

Sensor to Database: < 5000ms

Web Interface to MCU: < 5000ms

Alert Generation: ~2000ms, delivering timely user notifications for critical events.

E. Growth Enhancement

Preliminary trials showed a 20% increase in basil growth rate, attributed to precise environmental control and nutrient management. This validated the system's effectiveness in enhancing plant growth cycles.

VIII. CONCLUSION

The B.A.S.I.L. H.E.R.B. system combines advanced sensing, automated control, and web monitoring to create a user-friendly platform for indoor hydroponic herb growth. It manages lighting, nutrients, and environmental conditions to promote healthy plant growth with minimal effort. Initial trials show improved growth rates, validating the system's effectiveness. Future plans include adding machine learning and mobile support for greater accessibility and automation.

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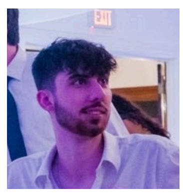
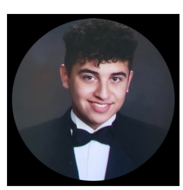
BIOGRAPHY

Casey O'Donahoe, graduating in computer engineering this semester, is a Software Engineer at Walt Disney Company with experience in solutions analysis, integration, and data analytics.



Logan Voiselle, graduating this semester with a bachelor's in computer engineering, aspires to build a long-term career with Lockheed Martin.

Justin Boyd is an electrical designer in the themed entertainment industry, a recent father, and a passionate hobbyist in electronics. He enjoys fishing, surfing, retro video games, and spending time with family.



Justin Press, graduating this semester with a bachelors of science in optical engineering, co-founded an Hire Match AI, where he leads technical development. He brings expertise in ML, LLMs, and advanced statistical methods, with plans to fully commit to the startup after graduation.