Independently Controlled Irrigation System for Agriculture Plots

Introduction

Problem:
Maintaining optimal environmental conditions for plant growth is essential for farmers, particularly those in rural farming lands where limited water supplies and lack of resources hinder productivity. Currently, both novice and experienced farmers/gardeners share a similar problem - different plant species require varying levels of soil moisture and ensuring each plant receives an ideal amount of water can be very time-consuming and error-prone. In modern day, most gardening enthusiasts manually cater their resources to each plant and this has proven to result in low-efficiency and lots of errors like under watering/overwatering plants. The concerns with modern-day irrigation plans is evident as underwatering/ overwatering plants cause significant issues like stunted plant growth and even plant death. Experiments highlighted by TreeNewal state that 80% of tree/plant problems can be attributed to the soil environment. According to the National Library of Medicine, 80-95% of the fresh biomass in plants is made up of water, highlighting the vital role water plays in a plant's growth, development, and metabolism. ScienceDirect further emphasizes that inconsistent watering and drought results in consequences like high salinity levels, heat stress, and attack of pathogens. This challenge becomes significantly more profound for farmers that have to monitor the specific water needs for different plant species.

The need for a precise, efficient, automatic irrigation solution is evident. Numerous countries across the world depend on the plant/crop yield of irrigated lands for resources like food. Clearly, inefficiencies and errors in the modern day manual irrigation have severe consequences as citizens of various countries are dependent on the plant's health and yield. According to the Food and Agriculture Organization (FAO), countries like India and Mexico depend on irrigated land for 55% of their agricultural output. As we can see, proper irrigation and watering systems are the key to high productivity in crop/plant outputs. The FAO also further highlights the need for a new automated watering system as currently, countries are spending a high amount of resources and money but are still not getting the results they want. For example, despite the high investments in the agriculture industry and improved irrigation, as much as 60% of the water diverted and pumped for irrigation is wasted. Smart, automated systems that can provide tailored irrigation for varying plant species are the next step in ensuring successful plant growth and assisting in combating real world crises like water scarcity.

References:
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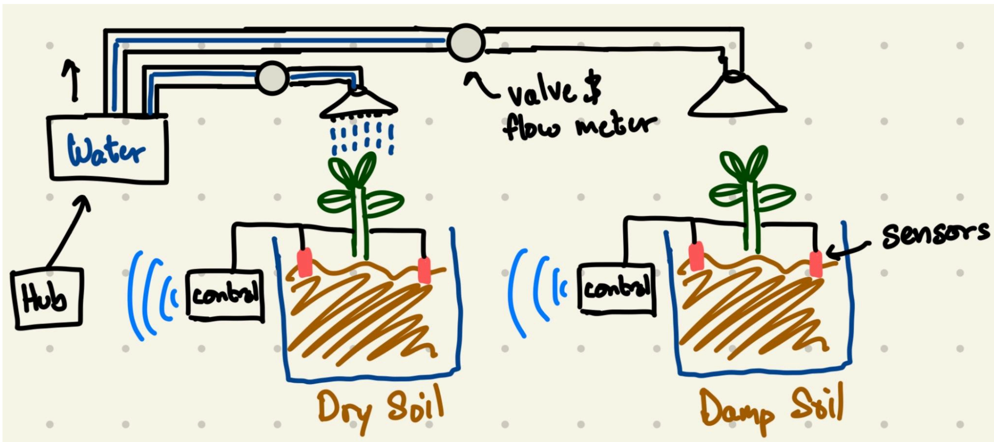
Solution:
Our solution aims to combat the inefficiencies and inconsistencies of modern-day irrigation approaches by creating a smart,automated watering system designed to cater to the needs of varying plant species. At the heart of this solution is a central water supply that is connected to each of the plants through its own valve. To prevent overwatering/underwatering, the most common issues when manually watering plants, each valve dispenses water based on real-time soil moisture data. This approach ensures that each plant receives the optimal amount of water and the correct times, and combats the issues in water waste and manual labor. By utilizing real-time data and automating the irrigation, we can eliminate the inevitable errors that come with human labor and significantly improve plant health/growth.

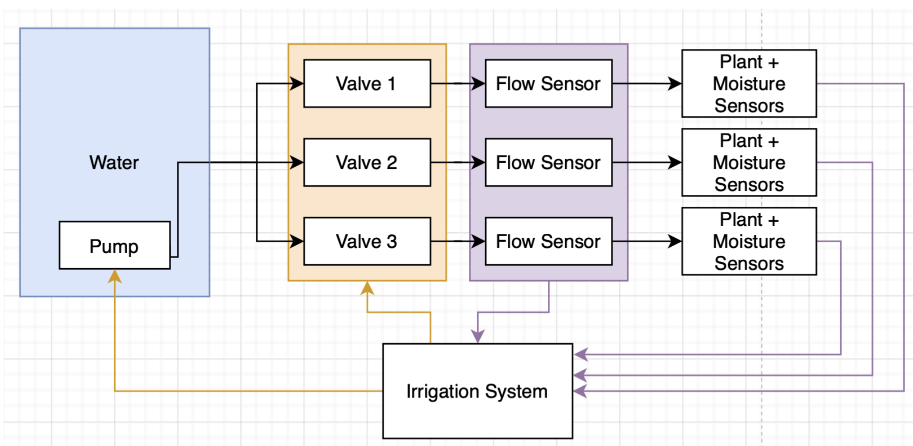
Our solution is split into 2 components, the irrigation system and the sensing system. The sensing system collects real-time data from the soil-moisture sensors to inform the irrigation system when and how much water each plant needs. Additionally, at the core, our solution includes a central microcontroller that will process the data from the soil sensors and can relay the information so the water valves provide the optimal amount of water to ensure precise and efficient crop growth. Our sensors will be distributed evenly across the soil in the plant environment and will be wirelessly transmitted to the control system via Bluetooth Low Energy. Our new irrigation solution will utilize Bluetooth Low Energy to transmit data as in rural area/farm lands WI-FI availability is minimal. In order to assist farmers that look to improve crop yield, we have taken account of the lack of available resources in the rural countryside. The control system processes data from the sensors and activates the irrigation system. The irrigation system includes pumps that use Pulse Width Modulation to regulate flow rate through the valves. Flow sensors will be integrated to deliver key information regarding water volume and flow rate to ensure the correct amount of water is delivered. We will include a user interface with React so users are enabled to adjust irrigation settings, track water usage in real-time, and customize watering schedules to their liking. This automated watering solution will ensure plants receive the perfect care without much human intervention, making it an ideal solution for managing diverse plant environments.

Our sensing system will also include humidity and temperature sensors to maintain the optimal soil moisture levels based on environmental factors. Given a plant's optimal soil moisture range (x% - y%), the microcontroller will use the readings from the soil moisture sensors and ensure water is dispersed so the current moisture level is in the middle of the optimal range. Then, considering the humidity and temperature sensors, our microcontroller will either adjust the water dispersed to make the moisture closer to x% or y%. If the environmental factors cancel out, then the microcontroller will disregard the humidity/temperature readings.

Example: We know that Basil has an optimal soil moisture range from 40-60%. Consider an example where our Soil Moisture Sensors show a current value of 50% moisture. If our humidity sensors depict a low humidity level and high temperature level, then we will disperse water so the moisture levels go closer to 60%. On the other hand, if our humidity sensors depict a high humidity level and low temperature level, then we will disperse water so the moisture levels go closer to 40%. Lastly, if our humidity sensors depict a high humidity level and high temperature level, then these environmental factors cancel out and our microcontroller only disperses water based on the soil moisture sensor.

Visual Aid:





High-Level Requirements List:

1) **Precise Water Delivery :** Upon recognizing low moisture levels in the soil, the system must activate the correct valve and deliver the optimal amount of water required. The system must release water at a rate of .5 - 2 liters per minute, depending on the current soil moisture levels.The flow sensor must indicate and verify that the water released is within +/- 3% of the requirement indicated by the current moisture level.

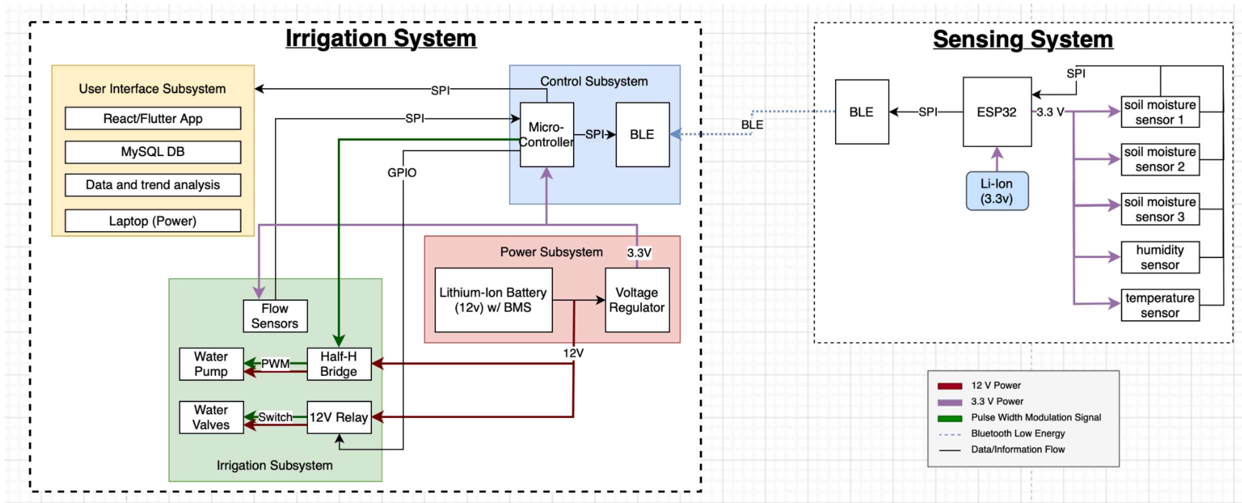
2) **Real-Time System Response :** A key feature of our solution is that human error is eliminated and the system is automated in real-time.The system must send moisture data to the ESP with a latency of no more than 5 seconds for continuous monitoring and quick data processing. The system must process data from the sensors and adjust water flow within the valves within 5-10 minutes of receiving the new data.

3) **Accurate Moisture Detection :**The system must measure and transmit soil moisture data from three independent sensors providing coverage of 1sq meter each. The sensors must transmit data with an accuracy of +/- 3% compared to the actual soil moisture levels. Then, the sensors must trigger a response to the control unit within 5 minutes if the moisture levels reach below a predefined threshold to initiate the watering cycle.

Sensing System Algorithm: First, set a predefined threshold for soil moisture based on plant-type and environmental factors. We will define the acceptable water flow rates and precision requirements as described above. Our data collection will continuously monitor and collect data from the independent sensors and each will transmit data to the microcontroller with low latency. If one of the 3 sensors provides data that deviates significantly (+/- 3%) we will recalibrate that sensor and have that sensor reprocess data. If the average moisture levels drop below the specified threshold, we will calculate the deficit between current moisture levels and target moisture levels and begin the irrigation process. We have also included humidity and temperature sensors that will fine tune how much water we are dispersing. The flow sensors will ensure that the irrigation system is delivering an accurate amount of water. After the irrigation system completes, our sensors will recalibrate and confirm the current moisture levels have reached the target. Once the soil moisture reaches the specified threshold, our microcontroller will close the valves and shut off the water system.

Design

Block Diagram:



* The User Interface System is powered by a mobile device or computer (not requiring system power).

Subsystem Overview:

Our project has two main systems: the irrigation system and the sensing system.

IRRIGATION SYSTEM

The irrigation system is the core of our project and includes subsystems that control the amount of water released, and when it is released. It also sends data to our user interface.

1. **Control Subsystem**

The control subsystem acts as the central hub of the irrigation system. It includes a microcontroller that processes inputs and outputs according to the program logic defined for irrigation. This subsystem uses the SPI (Serial Peripheral Interface) protocol to communicate with the user interface subsystem, and uses BLE (Bluetooth Low Energy) for wireless communication with remote sensor modules, receiving real-time soil moisture data. The control subsystem interprets these data points to manage the activation and deactivation of the water valves and pumps through the irrigation subsystem, thus maintaining optimal soil moisture levels across the garden.

2. **User Interface Subsystem**

The user interface subsystem provides an interactive platform for users to monitor and control the irrigation system. This subsystem is built with a React or Flutter application, enabling a robust and responsive user experience across various devices. Through this interface, users can customize watering schedules based on specific plant needs, view historical data to track water usage and soil moisture levels, and adjust settings to optimize water conservation and plant health.

3. **Irrigation Subsystem**

The irrigation subsystem is directly responsible for the physical delivery of water to the plots. It consists of a network of water pumps and valves controlled by the microcontroller in the control subsystem. The pumps use PWM (Pulse Width Modulation) signals to regulate the flow rate, while the valves, operated by switches, control the distribution of water to different sections of the garden. Flow sensors integrated within this subsystem provide feedback on water volume and flow rate, ensuring that each section receives the precise amount of water as instructed by the control subsystem. This feedback loop enables the system to adjust the water delivery dynamically, preventing overwatering or underwatering.

4. **Power Subsystem**

The power subsystem ensures that all components of the irrigation system have a reliable and stable power supply. It centers around a lithium-ion battery equipped with a Battery Management System (BMS), which helps in monitoring the battery's health and manages charging and discharging to extend battery life. The subsystem also includes a voltage regulator that steps down the 12V battery output to a stable 3.3V needed by the microcontroller and other low-voltage electronics. This setup supports the system's autonomy and allows it to operate in remote areas without direct access to electrical grids.

SENSING SYSTEM

The sensing system is an edge system placed in every pot/plot that needs to be monitored. It collects the data from the three sensor subsystems, averages the moisture levels, and broadcasts that data via BLE.

1. **Sensor Subsystem**

The sensor subsystem is centered around a capacitive soil moisture sensor, temperature, and humidity sensor connected to an ESP32 microcontroller. The sensor detects soil moisture by measuring changes in the soil's dielectric constant, which varies with the water content. This data is output as an analog voltage, proportional to the moisture levels. The wiring involves connecting the sensor's VCC pin to the ESP32's 3.3V power supply and the GND pin to ground. The sensor’s analog output is connected to an analog input pin, such as GPIO36, on the ESP32. The microcontroller reads these analog signals, scales them using its ADC (Analog-to-Digital Conversion), and interprets the soil moisture level accordingly.

2. **Power Subsystem**

The power subsystem utilizes a 3.3V lithium battery (e.g., a 18650 Li-ion battery) to supply power to both the ESP32 microcontroller and the soil moisture sensor. The battery is connected to the ESP32 through its VIN or 3.3V input pin, benefiting from the ESP32's built-in power management. In case the battery outputs a higher voltage, a voltage regulator is included to maintain a steady 3.3V supply. The soil moisture sensor shares this power supply with the ESP32, receiving power through its VCC pin. This ensures that both components are powered consistently throughout the operation.

3. **Control Subsystem**

The control subsystem is managed by the ESP32, which serves as the main control unit. It reads analog soil moisture data from the sensor and transmits the processed information to a central hub using Bluetooth Low Energy (BLE). The ESP32 operates as a BLE peripheral device, sending data either via advertisement packets or through GATT-based communication every 30 minutes. For scenarios involving multiple sensors, SPI communication may be employed for more complex data handling. The system is timed by the ESP32's internal clock, ensuring data transmission is spaced evenly. Additionally, TDMA scheduling can be implemented to avoid interference by ensuring that each sensor transmits data in its own designated time slot.

Subsystem Requirements:

IRRIGATION SYSTEM

The irrigation system is the core of our project and includes subsystems that control the amount of water released, and when it is released. It also sends data to our user interface.

1. **Control Subsystem**

- Must be able to receive and aggregate data every 5 seconds over BLE
- Must be able to calculate water necessary and respond with water for each plot within 30 seconds
- Must be positioned within range of at least one sensing system device for BLE
- Must be supplied power of 3.3V with a tolerance of ±0.1V

2. **User Interface Subsystem**

- Must update within 30 seconds of receiving data for each associated plot from control subsystem via SPI
- Must be capable of processing and storing up to one year worth of detailed data logs, and trends only for time before that

3. **Irrigation Subsystem**

- Water pump must operate within a voltage range of 10V to 12V and provide flow rates from 0.5 to 2 liters per minute.

- Valves must open and close in less than 1 second upon receiving a command via PWM to allow timely distribution of water
- Flow sensors must have an accuracy of within 3% to correctly report water delivery metrics back to the control subsystem for real-time adjustments with plants

4. **Power Subsystem**

- The lithium-ion battery must provide a continuous output of 12V ±0.6V with a capability to supply at least 500mA to the rest of the system
- The BMS must provide a supply of 12V ±0.6V to the pump and valves
- The voltage regulator must provide a stable output of 3.3V ±0.1V to ensure sensitive components like the microcontroller and sensors operate within safe electrical thresholds

SENSING SYSTEM

1. **Sensor Subsystem**

- Soil Moisture Sensors: Must measure soil moisture content within a 3% tolerance for accurate irrigation processes.
- Humidity Sensors: Must measure relative humidity levels within a 1% tolerance
- Temperature: Must measure temperature within a 0.5 C tolerance
- All sensors: Must operate at 3.3V and pull a maximum of 300mA (together)

Example of Sensing System:
We know that Basil has an optimal soil moisture range from 40-60%. Consider an example where our Soil Moisture Sensors show a current value of 50% moisture. If our humidity sensors depict a low humidity level and high temperature level, then we will disperse water so the moisture levels go closer to 60%. On the other hand, if our humidity sensors depict a high humidity level and low temperature level, then we will disperse water so the moisture levels go closer to 40%. Lastly, if our humidity sensors depict a high humidity level and high temperature level, then these environmental factors cancel out and our microcontroller only disperses water based on the soil moisture sensor.

Given a plant's optimal soil moisture range (x% - y%), the microcontroller will use the readings from the soil moisture sensors and ensure water is dispersed so the current moisture level is in the middle of the optimal range. Then, considering the humidity and temperature sensors, our microcontroller will either adjust the water dispersed to make the moisture closer to x% or y%. If the environmental factors cancel out, then the microcontroller will disregard the humidity/temperature readings.

2. **Power Subsystem**

- The lithium-ion battery must provide a minimum continuous voltage output of 3.3V and a current output of 300 mA to adequately power the microcontroller and sensor subsystem (with three sensors)

3. Control Subsystem
- Must be able to send data every 5 seconds over BLE once system is initialized
- Must be able to receive data every 15 seconds over SPI from sensor subsystem

TOLERANCE ANALYSIS

The power system needs to be carefully designed to ensure stable voltages for all the subsystems. The power subsystem contains a 12V battery but since our PCB requires a 3.3 V we need to use the LD1117 voltage regulator.

Since: $Vin > Vout + Vdropout$

$Vdropout = 1V\ (LD1117\ datasheet)$

$Vout = 3.3V$

$Vin = 12V$

Since V_{in} is greater than 4.3 V but lesser than 15V, we ensure that the output voltage will be 3.3V

The AQT15S solenoid valve operates at 12V with a 15% voltage range which means it can operate between 10.2V - 13.8V.
The valve will be connected to the microcontroller which operates at 3.3V but will need an Hbridge. Below is a table from the L9110 H bridge

Symbol	Parameters	minimum	Typical	maximum	units
VH_{out}	Output high	7.50	7.60	7.70	V
VL_{out}	Output low	0.35	0.45	0.55	V
VH_{in}	Input high	2.5	5.0	9.0	V
VL_{in}	Input low	0	0.5	0.7	V

On analyzing the table we can calculate the internal resistance.

$Vcc = 9V$

$Iout = 750mA$

Output high voltage $VHout = 7.6V\ (typical)$

$Vdrop = Vcc - VHout = 9V - 7.6V = 1.4V$

Using Ohm's Law: $Rinternal = \frac{Iout}{Vdrop}$

$Rinternal = 1.87\Omega$

The Hbridge outputs about 750mA ~ 800mA

The maximum voltage drop will be $Vdrop = IR$ (Ohm's Law): $800mA * 1.87\Omega = 1.496V$ $Vsolenoid = 12V - 1.496V = 10.504V$ which is more than 10.2V which will allow the solenoid to work as expected

Irrigation System:

1. SPI Clock Frequency Analysis

- The ESP32 can operate SPI at a maximum clock speed of 80 MHz when using SPI IO_MUX pins. However, for the purpose of this analysis, we are considering using a 10 MHz clock.
- The SPI protocol relies on clocking in data bits at each clock pulse. With a 10 MHz clock, the transfer rate is: Data Rate = $10\,MHz = 10 * 10^{6} bits/second$

2. Data Transfer Calculation

- Assume each soil moisture sensor provides 16 bits (2 bytes) of data per sample.
- If we have 3 sensors connected, the total data per transmission cycle will be:
- Total Data = $16\,bits \times 3 = 48\,bits$
- The time required to transfer this data at 10 MHz is:
- Transfer Time = $\frac{48\,bits}{(10*10^{6})} = 4.8\mu s$
- This means it takes only 4.8 microseconds to transfer data from 3 sensors using SPI at 10 MHz, which is extremely fast compared to the time needed for other operations.

3. Tolerance on Clock Frequency

- SPI requires a frequency tolerance to avoid data corruption. A ±5% tolerance on 10 MHz clock means the actual clock speed can vary between:
- Minimum Clock=10 MHz−(10×0.05) MHz=9.5 MHz
- Maximum Clock=10 MHz+(10×0.05) MHz=10.5 MHz
- The transmission time for 3 sensors at these frequencies would be:
  - At 9.5 MHz: Transfer Time=48 bits /(9.5×106 bits/sec)=5.052 μs
  - At 10.5 MHz: Transfer Time=48 bits/(10.5×106 bits/sec)=4.57 μs
  - The difference in transfer time is very small (±0.57 μs), meaning even with a 5% variation in clock frequency, the system can still relay data reliably.

4. Flow Rate Tolerance

- We will determine flow rate by testing 6 different voltage values on the valve and measuring the water output volume for each. We can then interpolate to confirm that we can output at least 0.5 L per minute. We will run this several more times to make sure our output is correct.

Even with a ±5% variation in the SPI clock frequency (ranging from 9.5 MHz to 10.5 MHz), the data transfer time difference is only ±0.48 microseconds. Since the system is designed to transmit data every 5 seconds, this small variation in transfer time will not impact overall system performance. The ESP32 can easily communicate with the central PCB in a timely and reliable manner, making the system robust for its irrigation tasks.

ETHICS AND SAFETY

Our optimized irrigation system should take into consideration the principles contained in the IEEE Code of Ethics including data confidentiality. The sensor system collects moisture levels as well as the amount of water consumed within a given period and this information may be sensitive and private to each farmer/gardener. We intend to use Bluetooth Low Energy (BLE) to transmit information ensuring safety of the communication and users will be sure that their data is classified. Furthermore, we want our solution to be available not only to gardeners looking to improve their plant growth but also for farmers looking to improve their crop yield in rural areas. This adheres to the principles of IEEE non discrimination and provision of equal opportunity. Lastly, considering the environmental impact of our solution, IEEE's principle is to comply with ethical design and sustainable development practices. Our solution inherently looks to reduce water waste and contribute to the sustainable development of agriculture. We will ensure that the components used in our solution are energy-efficient and environmentally safe. Our project will adhere to the Restriction of Hazardous Substances (RoHS) directives to eliminate hazardous materials from our system. We will do our due diligence to incorporate electronic equipment that doesn't have hazardous substances like lead,mercury, and cadmium.

According to the IEEE Code of Ethics, our design must hold paramount the safety, health, and welfare of the public. If there are faults in our irrigation system, crops may get damaged and lead to economic losses for farmers and gardeners. To abide by the IEEE Code of Ethics, we will install alert systems that will instantly notify users if a sensor or valve malfunctions in order to prevent over/under watering. Additionally, in our 3 Requirements to ensure our solution is successful, we have included tests to ensure the fail-safe precise nature of our solution. Finally, another concern may be the electrical safety of our project as we use microcontrollers and lithium-ion batteries. To avoid hazards like short circuits and water damage, we will ensure our project meets industry standards and certifications for electrical safety. We will make sure our solution is water resistant by including proper casing and isolation for components that may be exposed to moisture. To ensure electrical safety, we will follow the International Electrotechnical Commission (IEC) as they publish global standards for electrical and electronic technologies. We will follow the IEC standards to implement overcurrent protection circuits/fuses to prevent electrical overloads. We will also follow IEC standards and implement a Battery Management System to safeguard our lithium-ion batteries against overheating and thermal risks.