
Ultra-Low Power Soil Sensor Enabling Multi-Year Battery Life**Haryono¹**haryono@pradita.ac.id¹¹Universitas Pradita

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Abstract

Soil monitoring in large and remote agricultural areas is often limited by manual observation, resulting in low data frequency and reduced decision accuracy. To overcome this, this study presents a next-generation soil sensor system designed for ultra-low power operation and extended battery life. The system utilizes a STM32WLE5CCU6 microcontroller combined with a 6-in-1 RS485 soil sensor (T-H-EC-NPK) to measure soil humidity, temperature, electrical conductivity, and nutrient levels (N, P, K). The system operates using an optimized duty cycle, remaining in deep-sleep mode at approximately 3 μ A and periodically activating for a short 600 ms sensing and data transmission phase consuming around 150 mA. This approach significantly reduces average power consumption to approximately 0.028 mA. With a 4000 mAh battery and a transmission interval of one hour, the system achieves a theoretical lifetime exceeding 16 years. However, considering practical factors such as battery self-discharge, sensor overhead, and environmental conditions, the effective operational lifetime is conservatively estimated to exceed 5–10 years without battery replacement. The results demonstrate that the proposed design successfully enables long-term, maintenance-free soil monitoring, making it suitable for large-scale and remote precision agriculture applications where energy efficiency and system reliability are critical.

A. Introduction

Maintaining healthy turfgrass is essential for both the appearance and playability of golf courses. At Jagorawi Golf & Country Club—one of Indonesia's leading golf destinations—this task becomes more challenging due to its large area and diverse terrain. Located in the hilly region of Bogor, the course includes multiple sections with varying topography such as slopes, valleys, and dense vegetation.

Consistent turf quality requires regular monitoring of soil conditions, including moisture, temperature, and nutrient levels. However, conventional methods rely on manual inspection, which is time-consuming, limited in coverage, and unable to capture real-time changes effectively. Recent developments in precision agriculture demonstrate that data-driven monitoring can significantly improve irrigation efficiency and nutrient management [1], [4], [5], [10].

Wireless sensor networks (WSNs) have emerged as a practical solution for large-scale environmental monitoring in agriculture [1], [7], [8]. Among available communication technologies, Low Power Wide Area Networks (LPWAN), particularly LoRa, provide long-range communication with minimal energy consumption, making them suitable for outdoor and remote deployments [2], [3], [9]. LoRa-based systems have been widely studied for their scalability, reliability, and suitability in agricultural monitoring applications [3], [6], [9].

This paper presents a next-generation soil sensor system designed for multi-year battery life. The system integrates a low-power microcontroller with a multi-parameter soil sensor capable of measuring moisture, temperature, electrical conductivity, and nutrients (N, P, K). The use of efficient sensing strategies and low-power communication enables continuous monitoring with minimal energy consumption.

By combining optimized duty cycling and ultra-low power system design, the proposed system significantly reduces average energy consumption. This enables long-term operation with minimal maintenance, improving monitoring accuracy and scalability in large agricultural environments. The main contribution of this work lies in achieving multi-year battery life through efficient power management, demonstrating that long-term soil monitoring systems can be realized with practical and scalable design approaches.

B. Research Method

This study adopts a step-by-step engineering approach covering system concept, hardware development, integration, and validation. The proposed soil sensor node is based on the STM32WLE5CCU6 microcontroller combined with a RS485 T-H-EC-NPK sensor to capture essential soil parameters, including moisture, temperature, electrical conductivity, and nutrient content. The design prioritizes ultra-low power operation by leveraging deep-sleep states and short active periods for sensing and data transmission. Communication is carried out using LoRa to ensure stable long-range connectivity with minimal energy overhead. The sensing and transmission schedule is carefully arranged to reduce average current consumption and extend battery life over multiple years. System validation focuses on functionality, communication reliability, and energy

performance under realistic operating conditions, ensuring the solution is practical for continuous deployment in large outdoor agricultural environments.

B.1. System Design

The proposed system is designed as a compact and energy-efficient soil monitoring node. The main components include: STM32WLE5CCU6 microcontroller, combining processing and LoRa communication in a single low-power platform. RS485 T-H-EC-NPK soil sensor, used to measure soil moisture, temperature, electrical conductivity, and nutrient levels (N, P, K) with stable digital communication. Power system, consisting of a battery supply with optimized energy usage through deep-sleep operation and short active sensing cycles. LoRa gateway, responsible for receiving sensor data and forwarding it to a network server. Backend system, including a ChirpStack server and application server, which handle data processing, storage, and visualization for remote monitoring.

The overall design focuses on minimizing power consumption by carefully scheduling sensing and transmission intervals, allowing the system to operate reliably for multiple years without battery replacement.

B.2. Implementation

A working prototype of the soil monitoring node is developed by integrating hardware, embedded software, and network infrastructure. The system is built around the STM32WLE5CCU6 microcontroller, interfaced with a RS485 T-H-EC-NPK soil sensor for multi-parameter measurement. Firmware is designed to control periodic sensing, manage RS485 communication, and handle LoRa data transmission with minimal active time. Power optimization is implemented through aggressive use of deep-sleep mode and short wake-up intervals. The node communicates with a LoRa gateway, which forwards the data to a ChirpStack server and backend application for storage and visualization. The hardware is packaged to support outdoor deployment, ensuring stable operation under environmental exposure.

B.3. Testing and Evaluation

The system is evaluated through field-oriented testing to verify functionality, communication performance, and energy efficiency. Key aspects include the reliability of LoRa data transmission, consistency of sensor readings, and system behavior under periodic operation. Power consumption is observed across sleep and active phases to validate the effectiveness of the low-power strategy. In addition, long-interval transmission scenarios are tested to assess suitability for multi-year deployment. The results show that the system operates reliably, maintains stable communication, and achieves the expected low power consumption profile required for extended battery life.

C. System Architecture, Implementation, Testing, Result and Discussion

C.1. System Architecture

The proposed soil monitoring system is designed as a compact and energy-efficient sensing node focused on long-term autonomous operation. The architecture is centered on the STM32WLE5CCU6 microcontroller integrated with

a RS485 T-H-EC-NPK soil sensor. The sensor is responsible for measuring key soil parameters, including moisture, temperature, electrical conductivity, and nutrient levels (N, P, K).

The system operates using a periodic sampling mechanism. During each cycle, the microcontroller wakes from deep-sleep mode, activates the RS485 interface, collects sensor data, and prepares the data for transmission. After completing the sensing process, the system returns to low-power sleep mode. This cycle-based operation significantly reduces overall energy consumption while maintaining consistent data acquisition.

The architecture prioritizes minimal active duration, stable sensor communication, and efficient power usage, making it suitable for long-term deployment in outdoor environments without frequent maintenance.

C.2. Implementation

The hardware implementation is built around a low-power and compact design. The main components include:

- STM32WLE5CCU6 microcontroller, selected for its integrated LoRa capability and ultra-low power performance.
- RS485 interface circuit, ensuring stable communication between the microcontroller and sensor in outdoor conditions.
- Power system, designed to support long-term operation using battery supply with optimized consumption.

The hardware is implemented on a compact PCB with careful component selection to minimize power loss. Unnecessary loads are eliminated, and power lines are controlled to ensure efficient operation during both active and sleep states.

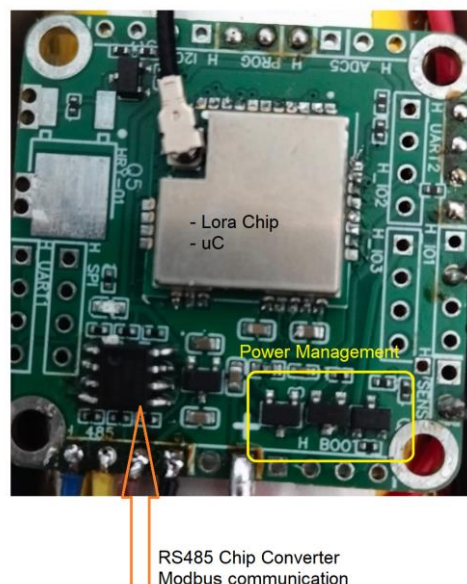


Figure 1. PCB Design - Hardware Result

The firmware is designed to manage sensing operations and power efficiency. Its main functions include:

- Periodic wake-up and sleep scheduling

- RS485 communication handling for sensor data acquisition
- Data processing and formatting
- Energy management through deep-sleep control

The firmware ensures that all operations are completed within a short active window, reducing the overall energy footprint of the system.

C.3. Testing and Evaluation

Measurement results show that the device consumes approximately 3 μ A (0.003 mA) in deep-sleep mode and around 150 mA during a 600 ms (0.6 s) active cycle for sensing and data transmission. The system operates with a transmission interval of one hour (3600 s).

The average current consumption is calculated using the duty-cycle model:

$$I_{avg} = (I_{active} \times t_{active} + I_{sleep} \times t_{sleep}) / T \quad (1)$$

Where:

$$I_{active} = 150 \text{ mA}$$

$$t_{active} = 0.6 \text{ s}$$

$$I_{sleep} = 0.003 \text{ mA}$$

$$T = 3600 \text{ s}$$

$$t_{sleep} = 3600 - 0.6$$

$$I_{avg} \approx (150 \times 0.6 + 0.003 \times 3599.4) / 3600 \quad (2)$$

$$I_{avg} \approx (90 + 10.8) / 3600 \quad (3)$$

$$I_{avg} \approx 100.8 / 3600 \approx 0.028 \text{ mA} \quad (4)$$

Thus, the average current consumption is approximately 0.028 mA.

$$\text{Lifetime (hours)} = \text{Battery Capacity (mAh)} / I_{avg} \quad (5)$$

$$\text{Lifetime} = 4000 / 0.028 \approx 142857 \text{ hours} \approx 16.3 \text{ years} \quad (6)$$

Therefore, the estimated battery lifetime is approximately 16.3 years.

Under ideal conditions, the system can theoretically operate for over 16 years. However, considering practical factors such as battery self-discharge, sensor overhead, transmission inefficiencies, and environmental conditions, the effective operational lifetime is conservatively estimated to exceed 5–10 years without battery replacement.

These results confirm that the proposed system achieves ultra-low average power consumption and successfully supports long-term, maintenance-free soil monitoring in real-world deployments.

C.4. Results and Discussion

The proposed soil sensor system was successfully developed and evaluated under real outdoor conditions. Field testing demonstrated stable operation across repeated sensing cycles, with consistent soil data acquisition and reliable RS485

communication. The system maintained proper functionality during continuous operation, confirming its suitability for long-term deployment in harsh environmental conditions.

Power measurement results indicate that the device consumes approximately 3 μ A during deep-sleep mode and around 150 mA for a short 600 ms active period during sensing and data transmission. Based on this duty cycle with a one-hour interval, the average current consumption is approximately 0.028 mA. This extremely low average power consumption enables a theoretical battery lifetime exceeding 16 years when using a 4000 mAh battery.

In practical scenarios, factors such as battery self-discharge, sensor overhead, and environmental conditions reduce the effective lifetime. However, the system is conservatively estimated to operate for more than 5–10 years without battery replacement. This demonstrates that the proposed design successfully achieves multi-year, maintenance-free operation.

The results confirm that ultra-low power optimization through duty cycling and deep-sleep strategies significantly reduces energy consumption while maintaining system reliability. This makes the solution highly suitable for large-scale and remote soil monitoring applications, where long battery life and minimal maintenance are critical requirements.

C.5. Hardware Implementation Result

Figure 2 shows the final prototype of the developed soil monitoring system. The system consists of two main components: the sensing unit and the control node, interconnected through a durable cable designed for outdoor deployment.

On the right side, the RS485 T-H-EC-NPK soil sensor is visible, equipped with three metallic probes that are inserted directly into the soil. This sensor is responsible for measuring multiple soil parameters, including moisture, temperature, electrical conductivity, and nutrient levels (N, P, K). The robust probe design ensures stable contact with the soil and reliable data acquisition under varying environmental conditions.

At the center, the control node enclosure houses the STM32WLE5CCU6-based circuit. The electronics are protected inside a sealed transparent casing, allowing visual inspection while maintaining protection against dust and moisture. Inside the enclosure, the microcontroller board, power regulation components, and communication circuitry are integrated into a compact layout. The visible LED indicator confirms active operation during testing and debugging.

The interconnecting cable on the left provides both power and data communication between the sensor and the control node using the RS485 protocol. The use of a thick, shielded cable enhances signal integrity and ensures reliable communication in outdoor environments.

Overall, the hardware implementation demonstrates a compact, robust, and field-ready design suitable for long-term deployment. The combination of a sealed enclosure, industrial-grade sensor, and low-power embedded system supports reliable operation in harsh conditions while maintaining the ultra-low power requirements necessary for multi-year battery life.



Figure 2. Fully Assembled Hardware Result

D. Conclusion

This study presents a next-generation soil sensor system designed for ultra-low power operation and multi-year battery life, integrating a STM32WLE5CCU6 microcontroller with a RS485 T-H-EC-NPK sensor for multi-parameter soil monitoring. The implemented hardware demonstrates a compact and robust design suitable for outdoor deployment, while experimental results confirm very low power consumption through optimized duty cycling, with approximately 3 μ A in deep-sleep mode and short 600 ms active periods at around 150 mA. Based on these measurements, the system achieves a theoretical battery lifetime exceeding 16 years using a 4000 mAh battery, and a practical operational lifetime conservatively estimated at 5–10 years when considering real-world factors. These results validate that the proposed approach enables reliable, long-term, and maintenance-free soil monitoring, making it highly suitable for large-scale and remote precision agriculture applications where energy efficiency and system durability are critical.

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