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Environmental Monitoring And Data Logging For Precision Irrigation Using An Embedded Sensor Platform

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ABSTRACT

Efficient irrigation management requires reliable information about environmental conditions that influence soil-water dynamics and crop water requirements. This study developed and evaluated a low-cost embedded sensor platform for environmental monitoring and time-stamped data logging to support precision irrigation. The platform integrated an Arduino Uno microcontroller with a DS18B20 soil-temperature sensor, DHT22 ambient temperature and relative-humidity sensor, DS3231 real-time clock, 16 × 2 I²C LCD and HC-05 Bluetooth module. The system was designed to continuously acquire environmental measurements, assign timestamps, display sensor readings and facilitate wireless access to recorded information. Sensor accuracy, temporal environmental variations, timestamp performance and wireless communication were evaluated over a seven-day experimental period. Soil-temperature measurements were acquired at 10-minute intervals. Soil temperature increased from 23.1 °C at 06:00 to 30.2 °C at 15:00, while ambient temperature increased from 24.6 °C to 33.5 °C. Relative humidity decreased from 82% to 46% during the same period. The DS18B20 produced an average absolute error of 0.32 °C, while the DHT22 showed deviations of approximately ±0.6 °C for temperature and ±2.5% for relative humidity compared with reference measurements. The DS3231 maintained timestamp accuracy within approximately ±2 s. Bluetooth communication achieved greater than 98% transmission success at approximately 10 m, with average latency below 300 ms. The findings demonstrate the feasibility of using low-cost embedded sensors for continuous, time-referenced environmental monitoring. The developed platform provides a practical foundation for precision irrigation research, environmental trend analysis and future development of data-driven irrigation models.

Keywords: Precision irrigation; Environmental monitoring; Internet of Things; Soil temperature; Relative humidity; Data logging

1. INTRODUCTION

Agriculture is one of the largest users of freshwater globally, making efficient water management essential for sustainable agricultural production. Irrigation is particularly important in regions where rainfall is seasonal, unreliable or insufficient to meet crop water requirements. Conventional irrigation practices often depend on fixed schedules or manual decisions, which may result in over-irrigation, under-irrigation, unnecessary energy consumption and inefficient use of available water.

Precision agriculture provides an alternative approach by using sensors, embedded systems, communication technologies and data-driven decision-making to respond to spatial and temporal variations in agricultural environments. The Internet of Things (IoT) has further enhanced this approach

by enabling agricultural sensors to collect, process and communicate field information in near real time (Ray, 2017; Wolfert et al., 2017).

Soil moisture is one of the most important parameters used for irrigation scheduling because it provides direct information about the availability of water within the soil. However, soil-water dynamics are also affected by environmental conditions including soil temperature, ambient temperature and relative humidity. Soil temperature influences root activity, microbial processes and evaporation, while ambient temperature and relative humidity influence atmospheric water demand and evapotranspiration. Consequently, integrating these environmental variables with soil-moisture measurements can provide a more comprehensive basis for irrigation management.

The development of low-cost sensing platforms has made environmental monitoring increasingly accessible to researchers and smallholder farmers. Microcontrollers such as the Arduino Uno can interface with several sensors and perform real-time processing at relatively low cost. Digital sensors such as the DS18B20 and DHT22 provide convenient measurement of temperature and humidity, while real-time clock modules such as the DS3231 allow measurements to be associated with accurate timestamps. Wireless modules such as the HC-05 can provide short-range communication between the embedded system and a mobile or computer-based monitoring device.

Previous studies have demonstrated the application of wireless sensor networks and IoT technologies to irrigation monitoring and control. Kim et al. (2008), for example, demonstrated remote sensing and control of irrigation using a distributed wireless sensor network. Ray (2017) highlighted the growing role of IoT technologies in agricultural monitoring, automation and decision-making. Similarly, Wolfert et al. (2017) emphasized the importance of reliable data acquisition and management for smart farming.

Despite these developments, many low-cost irrigation systems concentrate primarily on soil moisture and automatic pump control, with relatively limited attention given to synchronized environmental monitoring and local time-stamped data logging. A low-cost platform capable of recording environmental variables at defined time intervals can provide valuable information for understanding diurnal environmental patterns and developing improved irrigation strategies.

Therefore, this study developed and evaluated an embedded environmental monitoring and data-logging platform consisting of an Arduino Uno, DS18B20, DHT22, DS3231, LCD and HC-05 Bluetooth module. The specific objectives were to:

1. develop an integrated low-cost platform for environmental sensing and data logging;
2. measure temporal variations in soil temperature, ambient temperature and relative humidity;
3. evaluate the measurement performance of the DS18B20 and DHT22 sensors;
4. assess the timestamp stability of the DS3231 real-time clock;
5. evaluate Bluetooth communication performance; and
6. demonstrate the usefulness of synchronized environmental measurements for precision irrigation research.

2. MATERIALS AND METHODS

2.1 System Design

The monitoring platform was designed around an Arduino Uno microcontroller. The system consisted of five principal functional layers: sensing, processing, timing, display/data access and irrigation interfacing.

The sensing layer consisted of the DS18B20 soil-temperature sensor and DHT22 temperature and relative-humidity sensor. The Arduino Uno served as the central processing unit and received measurements from the sensors. A DS3231 real-time clock provided date and time information, allowing every observation to be associated with a specific timestamp.

A 16 × 2 I²C liquid-crystal display was used for local presentation of measurements, while an HC-05 Bluetooth module provided wireless transmission of the recorded information to a compatible receiving device. The platform was also designed to interface with the irrigation control subsystem through a relay.

2.2 Hardware Components

Component	Function
Arduino Uno	Central processing and control
DS18B20	Soil-temperature measurement
DHT22	Ambient temperature and relative-humidity measurement
DS3231 RTC	Accurate time and date recording
16 × 2 I²C LCD	Local display of sensor readings
HC-05 Bluetooth	Wireless data communication
Relay module	Irrigation actuator interface
Regulated power supply	Power provision to electronic components

2.3 Soil-Temperature Measurement

The DS18B20 digital temperature sensor was installed within the soil root-zone to measure soil temperature. The sensor was selected because of its digital output, simple microcontroller interface and suitability for distributed temperature measurement.

Soil-temperature observations were collected at 10-minute intervals. The recorded data were subsequently examined to determine changes in soil temperature during different periods of the day.

2.4 Ambient Temperature and Relative-Humidity Measurement

Ambient temperature and relative humidity were measured using the DHT22 sensor. The sensor was positioned above the soil surface in a location protected from direct solar radiation and excessive moisture while maintaining adequate exposure to surrounding air.

The measurements provided information about atmospheric conditions surrounding the experimental system. These variables were considered complementary to soil temperature and soil moisture because they provide an indication of environmental conditions influencing evaporative water loss.

2.5 Real-Time Data Logging

The DS3231 real-time clock was incorporated into the system to provide accurate date and time information. Each sensor reading was associated with the corresponding time of measurement.

The data structure consisted of parameters such as:

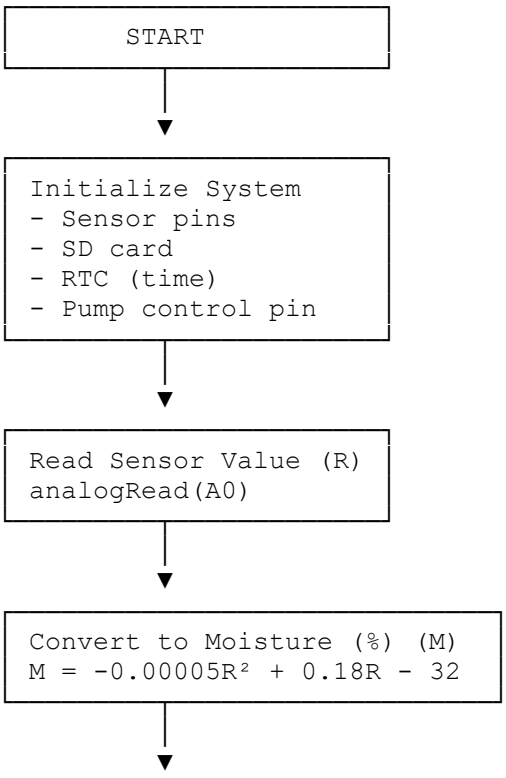
- date;
- time;
- soil temperature;
- ambient temperature;
- relative humidity;
- soil moisture, where available; and
- irrigation status.

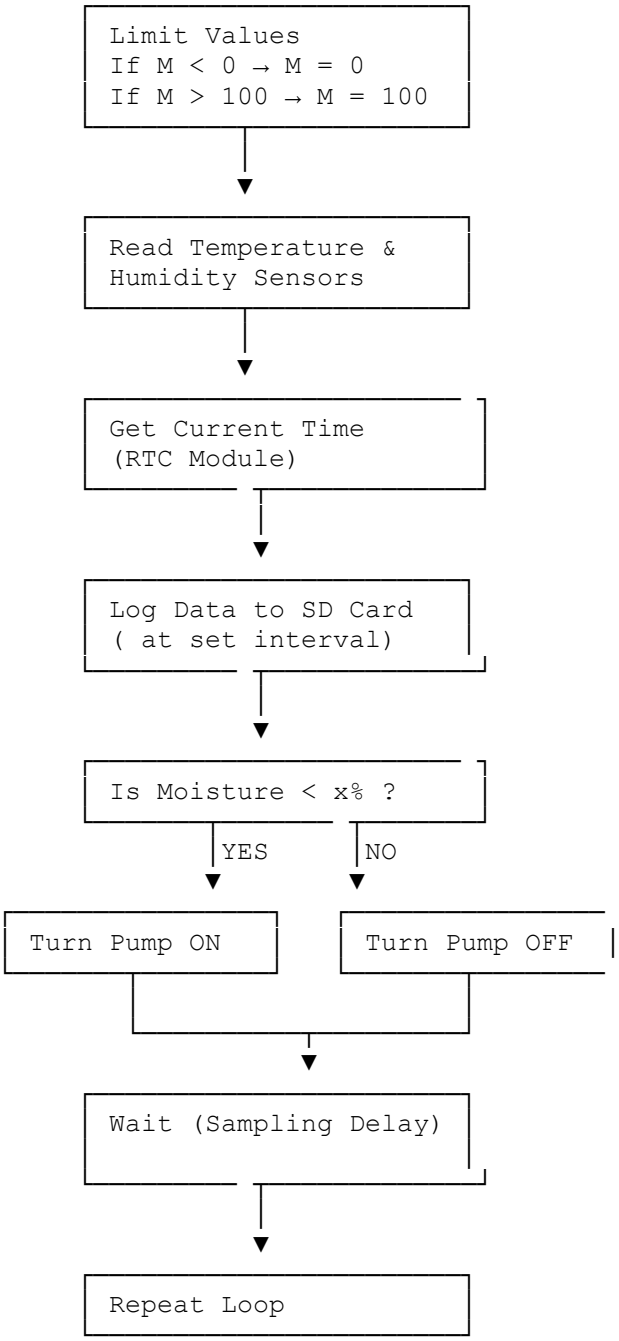
Time synchronization was particularly important because environmental variables change continuously throughout the day. Accurate timestamps therefore allowed measurements to be compared according to their actual time of occurrence.

The complete system is shown in Plate 1.

Plate 1: Complete system

Flowchart of the Smart Irrigation Program





2.6 Wireless Communication

The HC-05 Bluetooth module was used to provide short-range wireless communication. Sensor data processed by the Arduino were transmitted to a compatible receiving device.

Communication performance was evaluated at different distances. Transmission success rate and communication latency were used as indicators of wireless performance.

Transmission success was calculated as:

$T_S = NsNt \times 100$

where:

T_S = transmission success rate (%),

Ns = number of successfully received transmissions, and

Nt = total number of transmission attempts.

2.7 Sensor Calibration and Accuracy Assessment

The sensors were evaluated against reference measuring instruments. For each observation, the absolute error was determined using:

$$E_i = |X_i - X_{ref}|$$

whereX_i is the sensor measurement and X_{ref} is the corresponding reference measurement.

The mean absolute error (MAE) was calculated as:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|X_i - X_{ref}|$$

wheren represents the number of observations.
The sensor performance was assessed by comparing the recorded values with the corresponding reference measurements.

2.8 Experimental Procedure

The system was operated continuously over a seven-day experimental period. Soil temperature measurements were acquired at 10-minute intervals, while ambient temperature and relative humidity were monitored during the experimental period.
Representative environmental observations were examined at 06:00, 09:00, 12:00, 15:00, 18:00 and 21:00. The resulting measurements were used to examine the diurnal behaviour of the environmental variables.
The performance of the DS3231 was evaluated by comparing its recorded time with a reference time over the seven-day period. Bluetooth performance was evaluated at distances extending to approximately 12 m.

2.9 Irrigation Control Context

The environmental monitoring platform was integrated with an automated irrigation subsystem. A soil-moisture threshold of 30% was used as the representative control threshold. When measured soil moisture fell below the threshold, the controller initiated irrigation through the relay.
The irrigation response was assessed using the number of correct and incorrect irrigation decisions and the time required for the system to respond to a threshold crossing.

3. RESULTS AND DISCUSSION

3.1 Variation in Soil Temperature

The measured soil-temperature values showed a clear diurnal pattern.

Time	Soil temperature (°C)
06:00	23.1
09:00	25.4
12:00	28.6
15:00	30.2
18:00	27.5
21:00	24.8

Soil temperature increased from 23.1 °C at 06:00 to a maximum observed value of 30.2 °C at 15:00, representing an increase of 7.1 °C. The temperature subsequently declined to 27.5 °C at 18:00 and 24.8 °C at 21:00.The observed pattern is consistent with the expected response of soil temperature to daily solar heating. The gradual increase during the morning and early afternoon followed by cooling during the evening demonstrates the usefulness of continuous sensing compared with isolated manual measurements.

The DS18B20 produced an average absolute error of approximately 0.32 °C compared with the reference measurement. This level of deviation indicates that the sensor provided sufficiently stable measurements for environmental monitoring and irrigation research.

3.2 Ambient Temperature and Relative Humidity

Ambient temperature and relative humidity exhibited contrasting temporal patterns.

Time	Ambient temperature (°C)	Relative humidity (%)
06:00	24.6	82
09:00	27.8	68
12:00	31.2	54
15:00	33.5	46
18:00	29.1	63

Ambient temperature increased from 24.6 °C at 06:00 to 33.5 °C at 15:00. At the same time, relative humidity decreased from 82% to 46%.

The DHT22 showed deviations of approximately ±0.6 °C for temperature and ±2.5% for relative humidity compared with the reference measurements. These results indicate that the sensor was capable of providing useful environmental measurements for low-cost monitoring applications.

3.3 Soil Moisture and Irrigation Response

The environmental monitoring system was evaluated alongside the automated irrigation subsystem. A representative sequence of soil-moisture measurements showed a gradual decline during the day.

Time	Soil moisture (%)	Irrigation status
06:00	68	OFF
09:00	55	OFF
12:00	42	OFF
15:00	28	ON

The soil-moisture value declined from 68% at 06:00 to 28% at 15:00. When the measured value fell below the 30% control threshold, irrigation was activated at approximately 15:05.Following

approximately 20 minutes of irrigation, soil moisture increased to approximately 60%. This demonstrates the potential of combining environmental sensing with threshold-based irrigation control.

3.4 Irrigation Control Performance

During the evaluation, 26 irrigation events were recorded. All the 26 events were correctly identified and controlled, corresponding to a decision accuracy of approximately 100 %.

The average system response time was approximately 1.8 s.

The response time demonstrates that the embedded controller can react rapidly to changes in soil-moisture status. The result is consistent with the general potential of sensor-based irrigation systems to provide more responsive water management than conventional fixed schedules.

Kim et al. (2008) similarly demonstrated that distributed sensing and wireless communication can be applied to irrigation monitoring and control. More broadly, Ray (2017) identified IoT-enabled sensing and automation as important technologies for smart agricultural systems.

3.5 Real-Time Clock Performance

The DS3231 real-time clock demonstrated stable timing throughout the seven-day observation period. The observed timing difference remained within approximately ±2 s relative to the reference.Accurate timing is important in environmental monitoring because measurements without reliable timestamps are difficult to associate with specific environmental conditions. The use of a dedicated real-time clock therefore improves the quality of the environmental dataset and facilitates subsequent time-series analysis.

3.6 Bluetooth Communication Performance

The HC-05 module provided effective short-range wireless communication between the embedded platform and the receiving device.Communication testing showed greater than 98% transmission success at approximately 10 m, with average communication latency below 300 mS. The system remained practically stable at distances of approximately 10 m under the experimental conditions.

These results demonstrate that Bluetooth is suitable for local monitoring where the user or monitoring device is located relatively close to the irrigation system. However, Bluetooth is not intended to provide wide-area agricultural connectivity. Larger farms would require technologies such as Wi-Fi, LoRa, cellular communication or other long-range wireless systems.

3.7 Power Consumption

The electronic platform exhibited relatively low power requirements during sensing and data logging. Representative current consumption was approximately 65 mA during sensing and logging, increasing to about 95 mA during Bluetooth transmission. When the irrigation relay was active, the current demand increased to approximately 210 mA.

The relatively low consumption of the sensing and processing subsystem suggests that the platform could potentially be operated using a battery-supported solar power system. This is particularly relevant to agricultural environments where grid electricity may be unavailable or unreliable.

The results demonstrate that a low-cost embedded platform can simultaneously monitor soil and atmospheric environmental variables, assign accurate timestamps, display measurements and provide wireless access to recorded information.The integration of soil temperature, ambient temperature and relative humidity with soil moisture is particularly useful because irrigation requirements are influenced by both soil-water status and atmospheric demand. The platform therefore provides a foundation for moving from simple threshold-based irrigation towards adaptive and predictive irrigation systems.

The findings are also consistent with the broader literature emphasizing the importance of reliable data acquisition in smart agriculture. Wolfer*et al.* (2017) noted that agricultural data form an important basis for data-driven decision-making, while Kamilaris*et al.* (2017) highlighted the increasing importance of data analytics in agricultural systems.

4. CONCLUSION

A low-cost embedded sensor platform for environmental monitoring and time-stamped data logging was successfully developed and evaluated for precision irrigation applications. The system integrated an

Arduino Uno with a DS18B20 soil-temperature sensor, DHT22 temperature and relative-humidity sensor, DS3231 real-time clock, 16 × 2 I²C LCD and HC-05 Bluetooth module.The environmental measurements demonstrated clear daily variations. Soil temperature increased from 23.1 °C at 06:00 to 30.2 °C at 15:00, while ambient temperature increased from 24.6 °C to 33.5 °C and relative humidity declined from 82% to 46%. The DS18B20 produced an average absolute error of approximately 0.32 °C, while the DHT22 showed deviations of approximately ±0.6 °C for temperature and ±2.5% for relative humidity.

The DS3231 maintained timing accuracy within approximately ±2 s during the seven-day evaluation, while HC-05 Bluetooth communication achieved greater than 98% transmission success at approximately 10 m with average latency below 300 ms. The associated irrigation subsystem achieved 100% decision accuracy with an average response time of 1.8 s.

Overall, the developed platform provides a practical and relatively inexpensive approach for environmental monitoring and data logging in precision irrigation research. Its modular architecture also permits future integration of additional sensors and advanced decision-making algorithms.

Future development could include:

1. NPK sensing for monitoring soil nutrient conditions;
2. solar radiation and rainfall measurements;
3. improved soil-moisture calibration for different soil types;
4. long-range communication using LoRa, Wi-Fi or cellular technologies;
5. cloud-based data storage and remote monitoring;
6. evapotranspiration estimation;
7. machine-learning-based irrigation prediction; and
8. multi-season field evaluation under different crops.

These developments could transform the current monitoring platform into a more comprehensive precision-agriculture decision-support system.

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