Digital Twin Based Soil Moisture Measurement and Irrigation Optimization System

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Abstract. Digital twin technology has emerged as an effective solution for precision agriculture and water conservation. A Digital Twin based soil moisture measurement and irrigation optimization system is presented. The proposed techniques integrates multiple environment sensors, real-time monitoring and intelligent decision-making for efficient irrigation schedule. The proposed method uses sensos to collect data and process through Deep Forest-Based machine learning techniques for predicting soil moisture and irrigation requirements. The Deep Forest and Digital Twin methodology achieves overall prediction accuracy of 94.8% with irrigation success rate of 95.6%. The proposed approach offers a reliable, scalable and intelligent solution for sustainable agriculture, efficient water management and enhanced crop productivity.

Keywords: Sustainable, Smart irrigation, Virtual reality, Digital Twin

1 Introduction

In recent times, the world faces several challenges for sustainable living such as climate change, bio diversity, natural resource depletion, food security, scarcity of water, waste management, sustainable energy etc. The climate change and natural resource scarcity are major challenges that can affect the life of all living beings. Other side, the population of world is increased day by day and large number of resources in terms of water, food, energy will be required for fulfil the need of everyone. This research considers the water as natural resource and provide a sustainable system to conserve this resource. The water can be a primary resource for all living beings, agriculture and most of the industries. As the need for water grows, it is essential to adopt the cutting-edge technologies that can optimize water use in important sectors like agriculture, industry etc [1-2]. Further, it is observed that large amount of water is required in the field of agriculture. It is seen that most of the crops are not required too much water for irrigation and excess water may not fruitful for the growth of crops. Hence, an efficient water conserved system is needed to achieve the aforementioned task and can work in automated manner as well as remotely [3-4]. Hence, this research paper aims to develop a digital twin-

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based water conserve irrigation system for precision agriculture. Digital twin can be described as a gateway to the digital world in which virtual and real-world entities can be merged. In digital twin, the users can interact with virtual entities and environments, as well as connect with other entities in the shared virtual spaces based on virtual reality (VR) and augmented reality (AR) technologies. The digital twin is platform of technology, imagination, and human ingenuity. With the integration of the digital twin into the irrigation system, the proposed invention can efficiently manage the water for enhancing agricultural productivity as well as conserve natural resources in terms of water. This work presents the adaptability of digital twin into irrigation system and also eliminate the dependency on traditional irrigation system. This technology designs the smart and data driven system for efficiently conserve the water in agriculture. By leveraging the power of the digital twin, irrigation system is elevated to new levels, offering advanced monitoring, control, and collaboration capabilities. Through virtual representations, users can visualize their irrigation systems, monitor real-time data, and simulate the effects of different irrigation strategies. The digital twin serves as a hub for collaboration, allowing users to share insights, learn from experts, and collectively work towards water conservation.

2 Related Works

The smart irrigation technologies are playing important role in sustainable agriculture by controlled water management and increased crop productivity. This section addresses the various advancements done for making improvements in sustainable agriculture. Table 1 shows the related works that have adopted different methodologies for sustainable agriculture.

Table 1. Related works for sustainable agriculture

Approach	Input Parameters	Methodology Used	Reported Performance
Threshold-Based Irrigation [5]	Soil moisture	Uses soil moisture threshold values to turn irrigation ON/OFF	Water reduction observed for Tomato and Capsicum
Decision Tree [6]	Air temperature, Soil moisture, Relative humidity Time-related information	decision tree regression model was trained separately for field and forest soil types to estimate soil moisture values.	Performance was evaluated using Mean Absolute Error (MAE). Field soil achieved an MAE of 0.0019, while forest soil achieved an MAE of 0.0025.
Support Vector Machine (SVM) [7]	Soil moisture, weather, rainfall	Uses hyperplane-based classification/regression for soil moisture estimation	Accuracy around 81–85%; performs well for small datasets but struggles with nonlinear patterns (Springer)
Random Forest (RF) [8]	Soil moisture, temperature, rainfall, humidity	Ensemble of multiple decision trees; averages outputs for final prediction	Accuracy around 87%; stable and reliable with low overfitting (MDPI)

XGBoost / LightGBM [9]	Weather, soil, vegetation, satellite data	Gradient boosting models using sequential tree optimization	Best-performing traditional ML models with strong prediction capability and low error (ScienceDirect)
CNN[10]	Soil images, sensor grids	Extracts spatial features from soil images or sensor maps	Accuracy around 95.4%; good for spatial patterns but weak in time-series prediction (Springer)
LSTM[11]	Historical moisture, rainfall, weather data	Uses recurrent memory cells to learn temporal changes in soil moisture	Accuracy above 94%; RMSE below 0.035 in some studies; very effective for time-series prediction (HESS)
CNN-LSTM Hybrid [12]	Soil images, temperature, humidity, weather	Combines CNN for spatial features and LSTM for temporal dependencies	Accuracy around 98.5%; better than CNN or LSTM alone due to combined learning capability (Springer)
Graph Neural Network (GNN) [13]	Soil moisture from multiple nodes, weather	-Learns spatial and temporal relations among multiple field locations	Better handling of missing values and spatial correlations; useful for large farms (arXiv)
Deep Reinforcement Learning (DRL) [14]	Soil moisture, predicted water loss, crop condition	Learns optimal irrigation decisions through reward-based control	Achieved water savings up to 9.52% compared to conventional irrigation methods (arXiv)
Physics-Constrained Deep Learning [15]	Soil moisture, irrigation signals, soil physics	Combines physical water-transport equations with deep learning	Higher reliability and improved convergence compared to purely data-driven models (arXiv)

3 Proposed Methodology

This section presents the working of the proposed methodology for a Digital Twin based Soil Moisture Measurement and Irrigation Optimization System. Such irrigation system contributes for sustainable agriculture, water conservation, and improved crop productivity. The block diagram of the proposed architecture is shown in Figure 1. It is categorized into different modules defined as below.

- System Design Requirement: First module of the proposed Invention corresponds to estimate the irrigation requirements for a crop including various factors like climate condition, soil quality, crop and its life cycle. A thorough analysis on soil properties is conducted that determine moisture-holding capacity, drainage properties, and nutrient levels. Such information can be utilized for designing the effective irrigation planning and also overcome the water wastage occurred due to overwatering or poor drainage.
- Digital Twin Based Infrastructure: This module corresponds to installation of variety of sensor devices such as soil moisture sensors, PH sensor, humidity sensor, temperature sensor, air flow sensor, electronic sensor, accelerometer sensor, electrochemical sensors, soft water level-based (SWLB) sensors, contact sensors and carbon dioxide sensor etc., at

the strategic locations within the agriculture field. These sensors provide real-time data on climate, soil and crop conditions.Further, an irrigation infrastructure including drip irrigation systems, and micro-sprinklers are established in the agriculture land. This infrastructure aims to supply the water to the root of crops.After installing the sensors and establishing the irrigation infrastructure, a network infrastructure is designed to connect the sensors and transfer the data to the remote system. The collected data can be used for analyzing the water requirement and decision making.

- Soil Moisture Measurement and Optimization: This module corresponds to analyze the data collected from the various deployed sensor. This data is stored in a remote system and further, utilized to extract the information regarding the soil moisture. In this module, a deep forest-based technique is adopted for extracting the relevant information based on the input of the various sensors. Deep forest technique comprises of hierarchical structure of ensemble decision trees. This structure can be described through the deep architecture with multiple layers. Each layer contains a set of decision trees. The training process trains the decision trees at each layer with the help of training set. Further, the output of the previous layer is then used as input for the next layer. This hierarchical structure allows for capturing complex relationships and interactions between features in the data. In the prediction phase, the test data passes through the layers of decision trees. The final outcome is got by integrating the outputs of all the trees in the ensemble manner. The output of this module is defined in terms of the water irrigation requirement.
- Irrigation Optimization and Feedback System: After identification of water irrigation requirement, a threshold function is designed to schedule the irrigation task. The threshold function is combination of soil humidity sensor, temperature sensor and soft water level-based (SWLB) sensors. If the value is less than 0.5, then irrigation task will be scheduled in automated manner. Further, the feedback system also improves in timely manner by taking the input form remote monitoring and control, continuous monitoring and system maintenance and evaluation and improvement phases.
- Automated Control and Actuation: This module corresponds to an automated control system that can tune the irrigation parameters by using the analyzed data (Deep Forest) and optimizing the irrigation schedule. This module is also responsible for automatically control valves, pumps, and sprinklers to supply the appropriate amount of water at the right time.
- Remote Monitoring and Control: A remote monitoring and control feature can be integrated in the proposed invention based on either mobile or web-based application. This application enables farmers/Users to remotely access the real-time data regarding the crop and monitor system performance, and also provide valuable suggestions to make appropriate improvements.
- Continuous Monitoring and System Maintenance: This module corresponds to monitor the irrigation system in terms of sensor power, connectivity, irrigation infrastructure and optimizing irrigation schedule. The routine maintenance and calibration can responsible for optimal performance of the system in terms of water conservation as well as data collection.

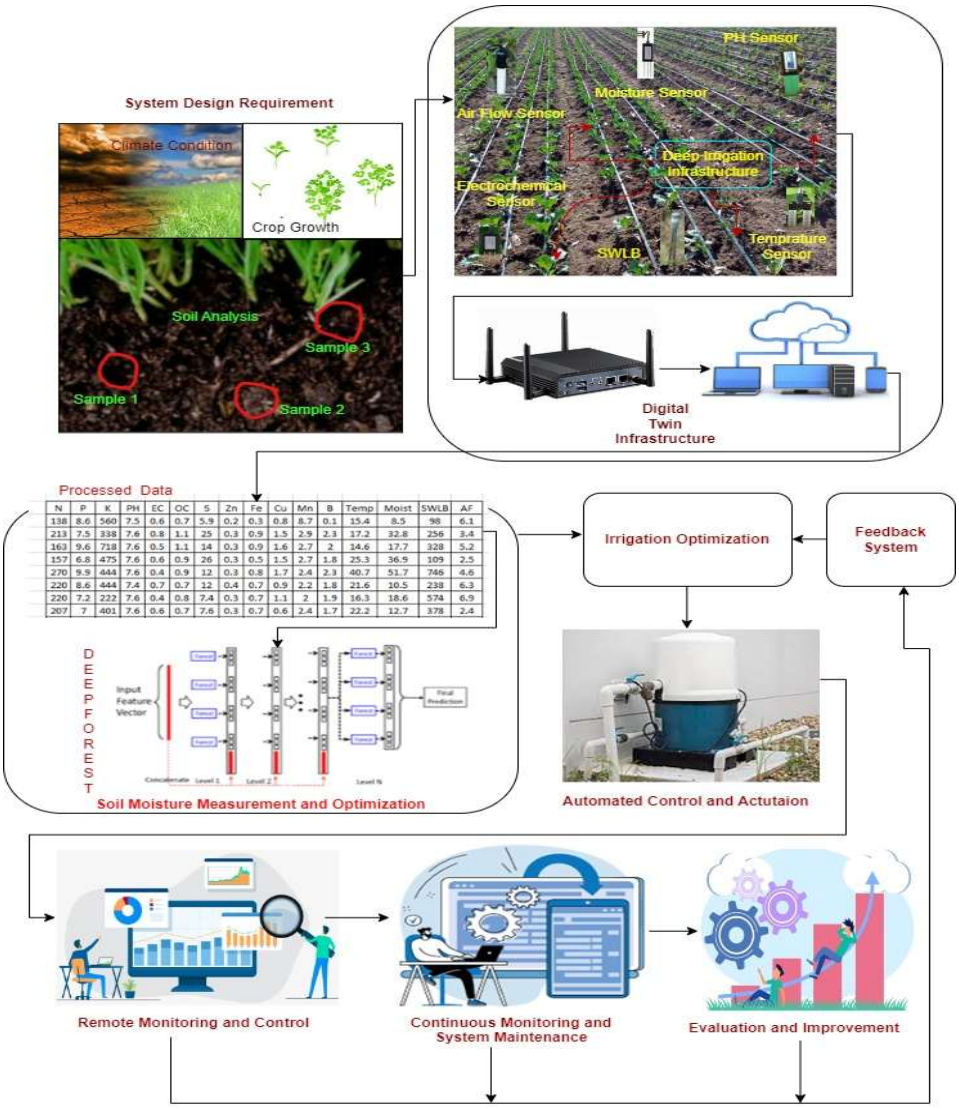


Fig. 1. Block diagram of the Digital Twin based Soil Moisture Measurement and Irrigation Optimization System

- Evaluation and Improvement: This module corresponds to evaluate the efficacy of the proposed invention in terms of water utilization. By analyzing the data and feedback from farmers can be taken into consideration for optimizing the water use in future for precision agriculture.

4 Experiment Results and Discussion

This section shows the comparison of different methods and the proposed digital twin methodology. It has been observed that the proposed model attains the highest prediction accuracy of 94.8% as shown in Figure 2. The proposed method outperforms the traditional threshold-based methods and common machine learning models.

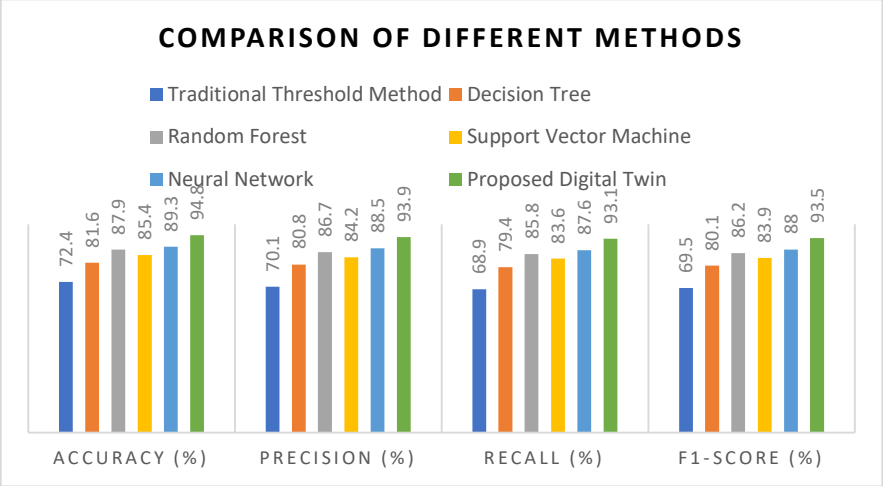


Fig. 2. Soil Moisture Prediction Accuracy Comparison

The proposed system significantly reduces water usage by automatically scheduling irrigation when the threshold value falls below 0.5. This helps prevent overwatering and improves crop productivity. Figure 3 shows the sensor-wise performance in soil monitoring. For all types of sensors used in the proposed methodology, it is seen that the soil moisture sensor gives highest accuracy as it measures soil water content directly. The use different sensors help improve the overall reliability in the decision making of the irrigation process.

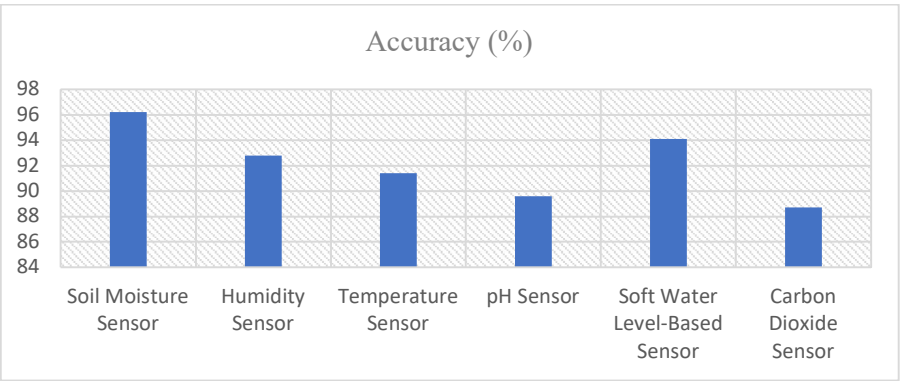


Fig. 3. Sensor-wise performance in soil monitoring

5 Conclusion

A Digital Twin based Soil Moisture Measurement and Irrigation Optimization System provides an intelligent and efficient solution for precision agriculture. The use of real-time sensor data, remote monitoring, automated irrigation infrastructure; the system can accurately estimate soil moisture and optimize water usage. Such continuous monitoring of soil and crop conditions can help the farmers in making timely decisions. Thus, the proposed system contributes for sustainable agriculture, water conservation, and improved crop productivity. The proposed system achieves accuracy of 94.8% and reduced irrigation as compared to other techniques. The digital twin-based irrigation method offers a sustainable, scalable solution for conserving water resources and improving crop productivity.

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