



Original Research Article

Design, Simulation and Fuzzy Logic Controller of Smart Drip Irrigation System for Enhanced Water Use Efficiency and Crop Productivity

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ABSTRACT

Smart irrigation systems play a crucial role in optimizing water usage for sustainable agriculture. This paper presents the design, simulation, and fuzzy logic control of a smart drip irrigation system that integrates soil moisture sensors, soil temperature sensors, a humidity sensor, and an automated control mechanism to enhance water efficiency. The proposed system used a proportional-integral-derivative (PID) to regulate the amount of water and a fuzzy logic controller (FLC) to make decisions on when to irrigate or when not to irrigate and automatically regulate water flow based on a predefined threshold. The system was designed using Proteus software, and Matlab/Simulink was used to develop and simulate the system. The result of the proposed system showed the effectiveness of the smart drip irrigation system in reducing water consumption while maintaining optimal soil conditions for healthy plant growth. Comparative analysis with a conventional irrigation system demonstrated a significant reduction in water wastage. The result also indicated that the smart drip irrigation system can contribute to sustainable farming practices, improved crop yield, and resource conservation.

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1. INTRODUCTION

In the face of escalating global water scarcity and the pressing need for sustainable agricultural practices, the integration of smart technologies into irrigation systems has become paramount (Santos et al, 2023). Water is one of the most essential resources and variables for conducting agricultural activities, especially when compared to other natural resources like soil. Research indicates that the agricultural sector worldwide consumes approximately 70% of accessible freshwater each year to irrigate merely 25% of fertile land (Lakhier et al, 2024).

In Nigeria, as in many developing countries, agriculture is the predominant occupation and currently has numerous challenges due to insufficient water supplies, particularly during arid seasons. With rapid population growth and rising unemployment, ensuring adequate water availability has become imperative for improving agricultural productivity. In crop production, sustained agricultural output depends on the consistent supply of sufficient quantities of freshwater, which can only be effectively achieved through a properly regulated irrigation system (Ihendinihu and Inyama, 2023).

Irrigation is a crucial element in enhancing crop productivity and sustaining agricultural practices throughout all seasons. Irrigation is the method of supplying supplementary water, beyond natural precipitation, to the soil to facilitate or improve plant development and yield, as well as, in certain instances, the volume of foliage or harvested plant components. Currently techniques used for irrigation in Nigeria include manual irrigation such as furrow, basin, rooftop and watering can. These techniques remained ineffective with low performance because they are intended only to control the distribution of water at required locations without investigating and considering real time water requirements (Odo and Abonyi; 2023, Odo et al, 2024).

The shortage of water and the increasing demand for food production have rendered efficient water management in agriculture an essential issue. Conventional irrigation techniques frequently result in considerable water loss and inadequate crop production, posing obstacles to sustainable agriculture (Oaishe et al., 2023; Wu et al., 2023; Marimuthu et al., 2024). There is potential to improve water use efficiency with smart irrigation systems, especially with the advent of monitoring systems and advanced management tactics (Bwambale et al, 2022).

Simulation plays an important role in design and modeling of smart drip irrigation system. By modeling various environmental parameters and system configurations, simulation can predict system performance, identify potential issues and guide the development of efficient irrigation strategies (Dmitriy and Andrii, 2020).

The adoption of smart drip irrigation systems is particularly advantageous in regions facing water limitations and those striving for sustainable agricultural intensification. By minimizing water waste and optimizing crop yields, these systems contribute to food security and the conservation of natural resources (Bakare, 2022).

The integration of smart technologies into drip irrigation systems has become a focal point in advancing sustainable agriculture. A research work carried out by Edralin et al (2023) examined smart irrigation for sustainable agriculture: A framework for the IoT-enabled drip irrigation system. They looked into how possible it is to use automated drip irrigation to save water and make farming and production better. Qualitative research methods, like in-depth interviews and observations with local farmers, municipal agriculturists, and agricultural engineers, were employed to acquire vital data for validation. Using the three tiers of IoT architecture, data from the natural environment was collected and analyzed. The data was utilized to govern how the actuators performed. The architecture that has been built made it simple to develop low-cost, straightforward IoT-driven crop farming. However, the research was based on the framework for IoT-enabled drip irrigation system. A study by Bakare et al, (2022) presented a smart irrigation system utilizing sensors such as light, temperature and soil moisture to monitor field conditions. The system employs a PIC18F4620 microcontroller to process sensor data and control irrigation accordingly, ensuring optimal soil moisture levels for crop growth. Similarly, a systematic review by Vallejo-Gomez et al, (2023) highlighted the application of artificial intelligent (AI) in smart irrigation systems. The study emphasized the role of AI in analyzing environmental data to make informed irrigation decisions, thereby conserving water and enhancing crop productivity. However, the research work was based on systematic review as no physical implementation was carried out. Research by Naziq et al, (2024) discussed the coupling of weather and crop simulation models to optimize irrigation scheduling. The study suggested that transitioning from traditional gravity surface irrigation to pressurized systems like drip irrigation can simplify scheduling and improve water use efficiency. Despite the good work done by these researchers, the work concentrated only on review as no implementation was carried out. In the work of Lakhia et al, (2024) titled a review of precision

irrigation water-saving technology under changing climate for boosting water use efficiency, crop productivity, and environmental footprints. The authors proposed that the adoption of precision irrigation water-saving systems (PISs) for efficient water management under climate change is a highly recommended method farmers should engage themselves in. It can reduce the detrimental effects of changing climate and help boost water use efficiency, crop productivity, and environmental footprints. Their study was meant to completely evaluate and review PISs, concentrating on their creation, implementation, and beneficial impacts on sustainable water management. The research showed that as the water scarcity problem intensifies due to climate change and population growth, the PIS is poised to play a critical role in optimizing and modernizing water usage, increasing water use efficiency, and reducing environmental footprints, thus ensuring sustainable agricultural development.

A review of existing related studies revealed significant knowledge gaps in current irrigation control systems. In response to these identified gaps, this research focuses on the design and simulation of a smart drip irrigation system aimed at promoting sustainable agricultural practices. This smart drip irrigation system, which combines precise water delivery and automated control mechanisms, offers a viable solution to the challenges faced by traditional/conventional irrigation systems. The system utilizes a network of soil moisture sensors, environmental monitors, and automated controllers to deliver water directly to the root plant zone, ensuring optimal hydration while minimizing waste.

2. MATERIALS AND METHODS

The materials required for this research work are divided into hardware and software tools. Hardware tools include Arduino Nano microcontroller, YL-69 capacitive soil moisture sensor, LM35 soil temperature sensor, temperature and humidity (DHT22) sensor, solenoid valve, drip irrigation pipes emitters, power supply and relay module. The software tools include Proteus 8 simulation software and Matlab/Simulink computing software.

2.1 Methodology

2.1.1. Design method

The design process follows a sequential method which involves a detailed circuit diagram which shows the interconnection of the individual components that make up the hardware phase of the system, fuzzy inference system and the developed Matlab/Simulink model of the system.

2.1.2. Circuit diagram of the system

The circuit diagram shows how the various parts of the main electronics hardware system are connected. It is intended to be used as a guide when assembling the physical parts of the hardware subsystem, the circuit diagram was created using Proteus 8 simulation software. The circuit diagram of the smart drip irrigation system is shown in Figure 1.

The smart drip irrigation system consists of a network of sensors that monitor soil moisture content, temperature, and humidity levels. The sensor nodes were linked to a central node (an Arduino Microcontroller Board), which is in charge of gathering data from the sensors and transmitting it to the ESP32 Wi-Fi module which is responsible for uploading the data to the online Database for cloud-based data storage. To operate the hardware, a software program was created to run on the Arduino and ESP32 microcontrollers. The hardware components of the system were positioned close to the plant to feel its surroundings, and it was wirelessly connected to the main station through an ESP32 microcontroller that serves as the main wireless data transmission channel. The main data collection station collects the data and processes the sensor values based on the C++ instruction that has been programmed on it. It also enabled the Arduino to initiate a serial communication with the ESP32 through the serial ports. After receiving the data from the microcontroller, the ESP32 then connects to Wi-Fi network to transmit data to an online MySQL database from which the data can be displayed in real-time and viewed remotely on a custom web dashboard. The average monthly real-time data collected

from the tomato farm located at Michael Okpara University of Agriculture, Umudike, was inserted into the Simulink developed model of the smart drip irrigation system.

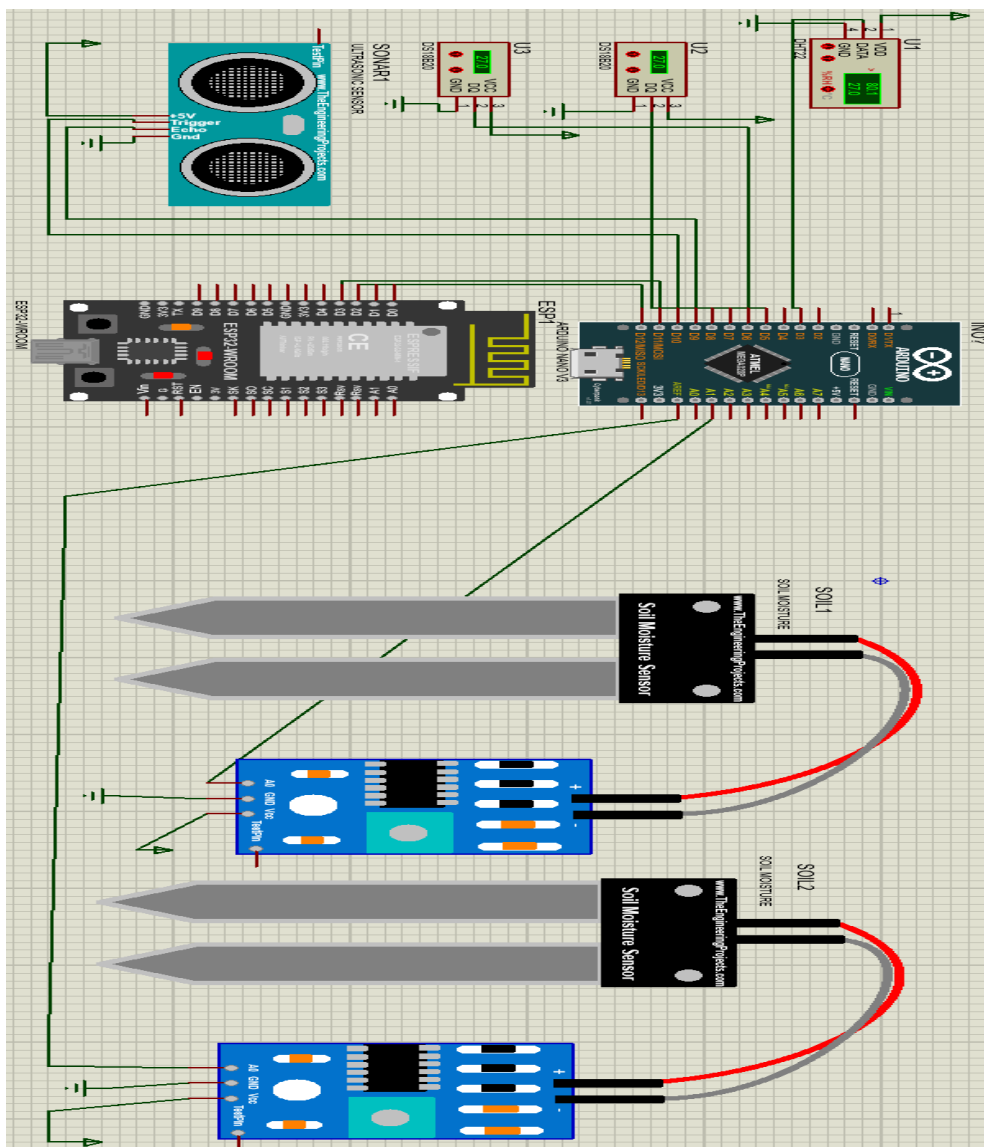


Figure 1: Circuit diagram of the smart drip irrigation system

Also, the average monthly data obtained from the traditional/conventional irrigation was inserted into the Simulink developed model of the conventional irrigation system. These data were simulated in the Matlab environment and the results of the simulation were compared for smart drip and conventional irrigation systems. Also based on the C++ program instruction, the Arduino microcontroller was able to evaluate the sensor reading especially the reading from the soil moisture sensor and used the result of this evaluation as a guide to either turn on or turn off the solenoid valve through a relay module.

2.1.3. Fuzzy inference system (FIS) editor

The names of the defined input variables are given at the top left of the fuzzy inference system, and the output variable is shown at the right of the system. The membership functions are located in the boxes and system name and the Mamdani inference method used are also indicated. The Mamdani-type inference which formulates a mapping from a given input to an output using fuzzy logic is used as the inference engine. Figure 2 shows the MATLAB interface implementing the model.

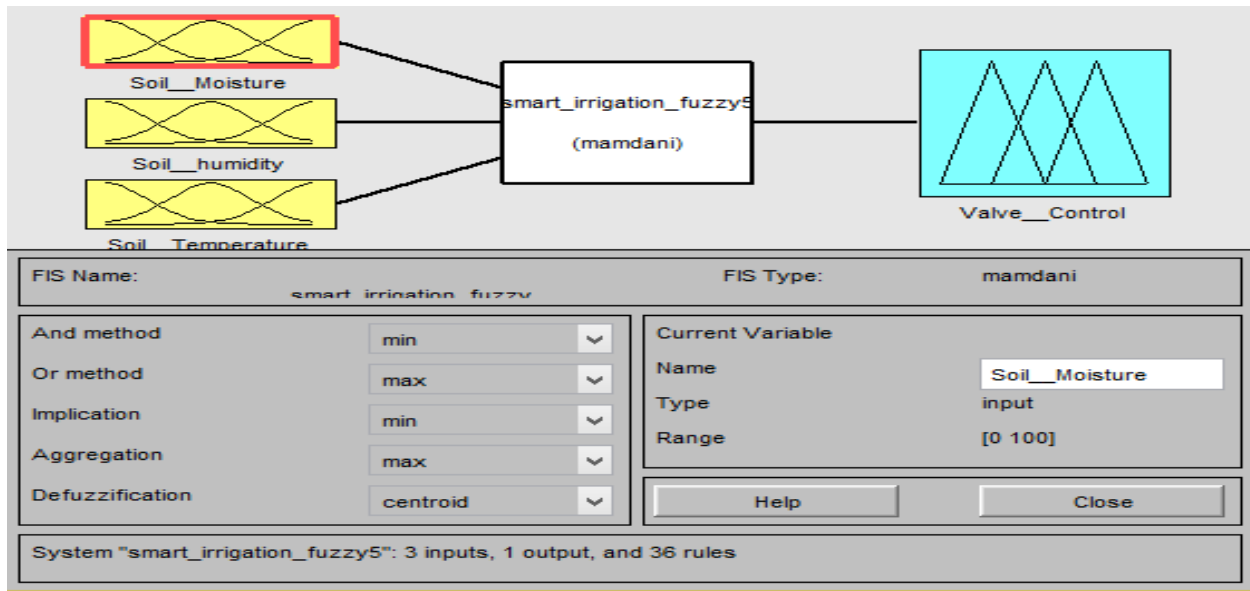


Figure 2: Fuzzy inference system

2.1.4. Membership function (MF) editor

A membership function (MF) is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership (μ)) between 0 and 1. The input space is sometimes referred to as the universe of discourse. The membership functions are selected for each fuzzy input and output variable based on the fuzzy set mentioned above. The membership functions (MFs) for soil moisture, soil temperature and humidity are shown in Figures 3, 4, and 5 respectively.

2.1.5. Production output membership function

The production output membership function consists of five linguistic terms: (irrigate fast, irrigate slowly, do not irrigate, irrigate lightly and irrigate heavily), two linguistic and the MATLAB interface implementing the production output membership function is shown in Figure 6.

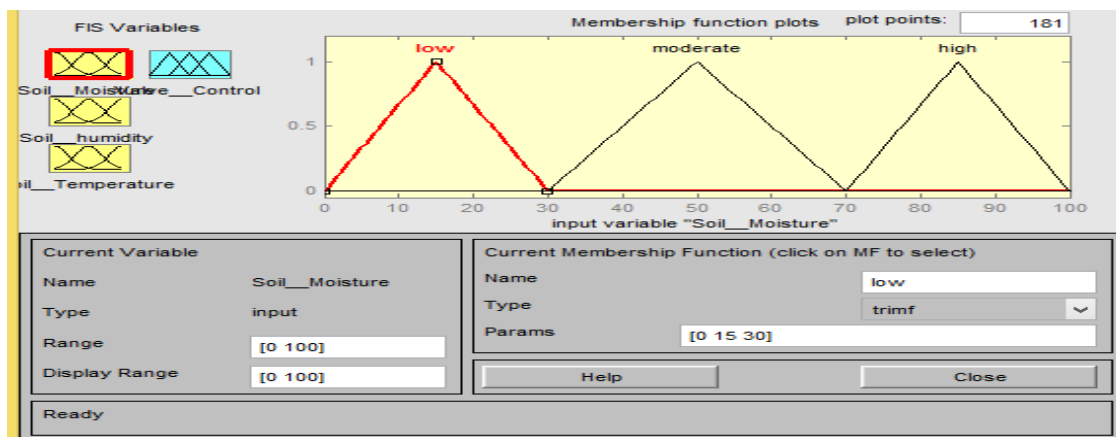


Figure 3: Soil moisture membership function

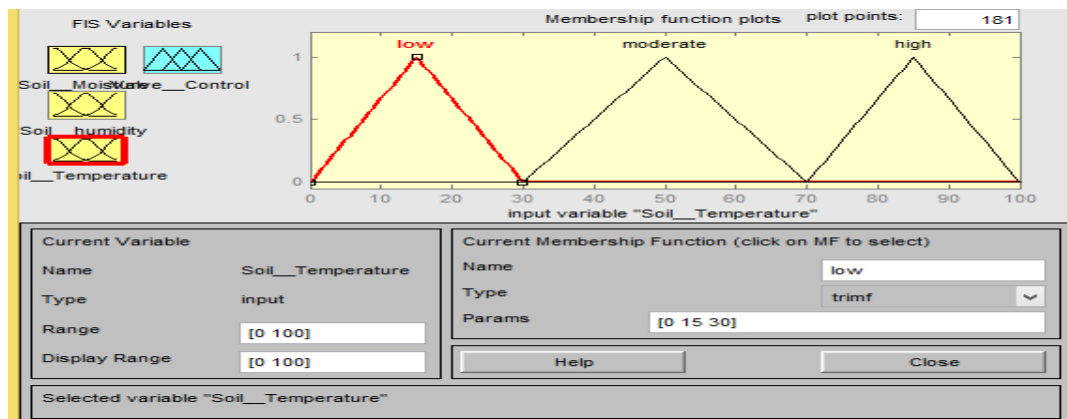


Figure 4: Soil temperature membership function

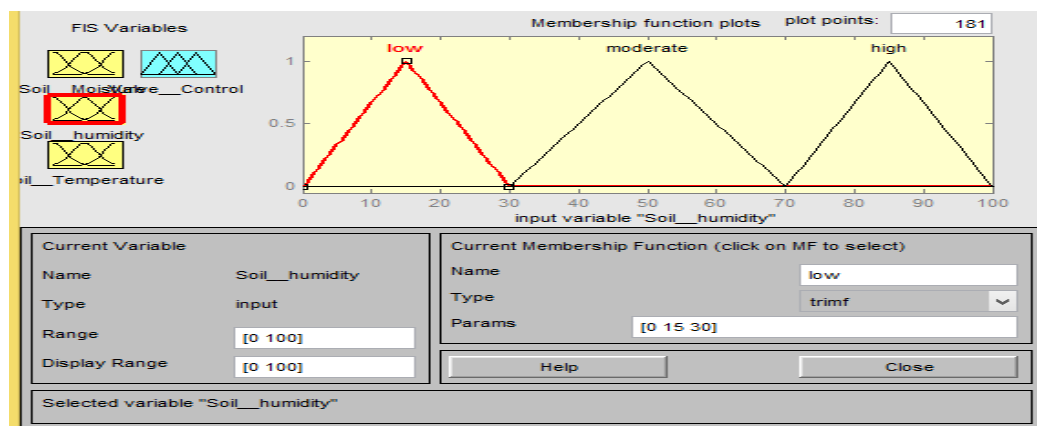


Figure 5: Soil humidity membership function

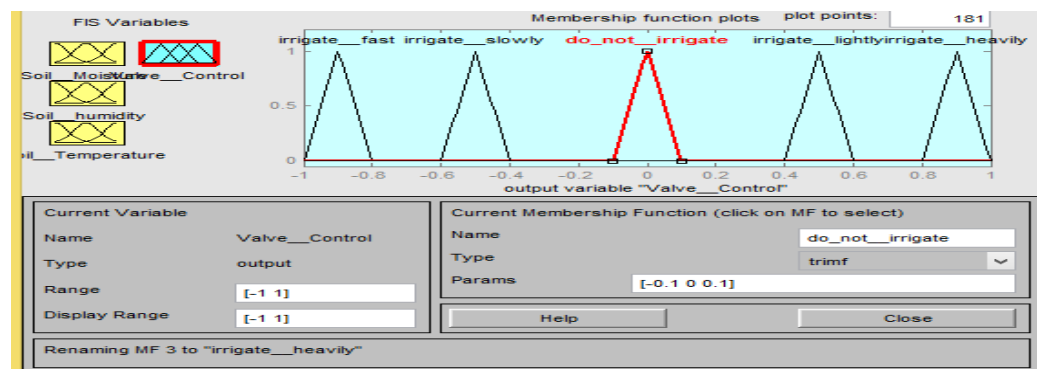


Figure 6: Membership function of the production output

2.1.6. Smart irrigation system fuzzy rule editor

Fuzzy rule base is the heart of the fuzzy inference system (FIS). This performs the actual mapping or inferencing between the input and output fuzzy sets. The fuzzy rule base is collection of rule curves represented in the form of linguistic variables. A rule is represented in the form of an IF-THEN statement. Once the rule matrix was designed and the fuzzy variables are defined in the fuzzy inference system editor, construction of the actual rules by the rule editor was easy. The logical connectives of rules, AND, OR and NOT can be selected by buttons. The rules can be changed, deleted or added as desired.

In this study, soil moisture, soil temperature and soil humidity were considered as the input variables for environmental conditions, intruder detector as security and production output which is the control of solenoid valve and the security was considered as the output variable. The relationship between the input variables and the output variable is represented in fuzzy set notation in Equation 1 as;

$$PO = SL \cup ST \cup H \quad (1)$$

It follows that; Production Output (PO) = {soil moisture} and {soil temperature} and {humidity}

The above notation is used when fuzzy rules are written to associate fuzzy input variables with the fuzzy output variable. Since there are 3 subsets for soil moisture, 3 subsets for soil temperature, and 3 subsets for humidity, it means that a total of 27 rules can be composed with reference to a Figures 3, 4 and 5 above that is (3*3*3=27). The MATLAB interface implementing the various rules used for evaluating the system is shown in Figure 7.

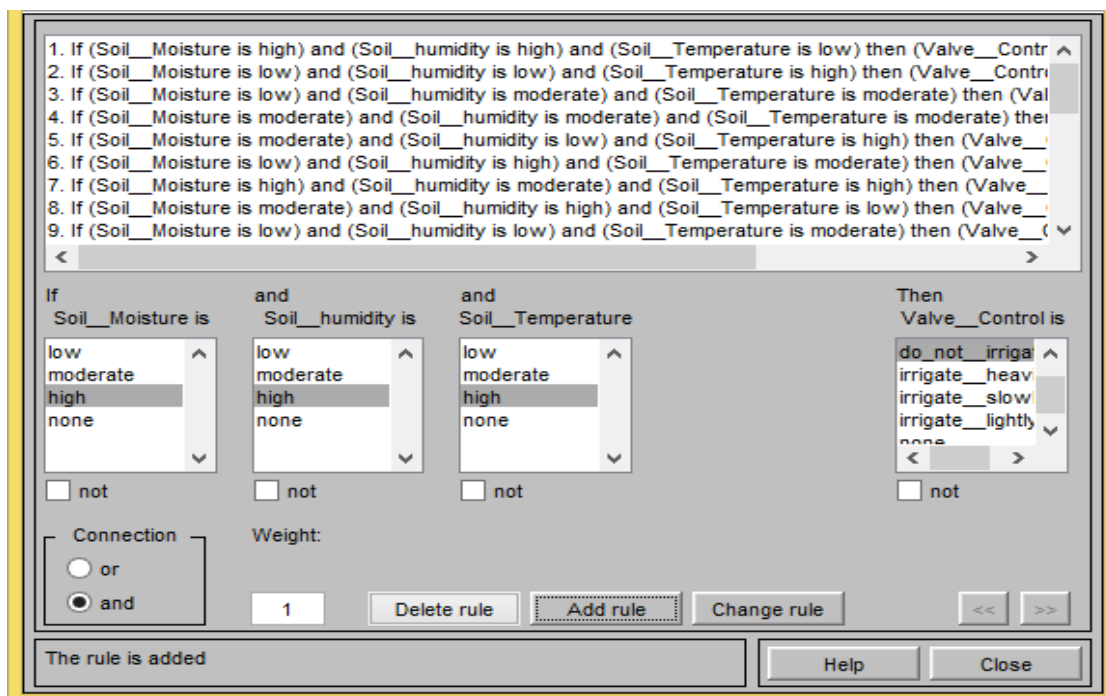


Figure 7: Screenshot of rules defined in MATLAB

2.1.7. Developed Simulink model of conventional and smart drip irrigation systems

Figures 8 and 9 illustrate the developed Simulink models for both smart drip irrigation system (SDIS) and conventional irrigation system (CIS). The manual input blocks allow user defined input for soil moisture, soil temperature and humidity. These inputs were fed into a signal processing unit, which ensures standardized sensor readings before further processing. The conversion block normalizes and processes raw sensor data and the threshold based logic determines whether soil moisture level requires irrigation. The comparator compares real-time sensor values with predefined threshold value to trigger control actions. The control and decision making unit, which comprises of PID and fuzzy logic controller receives processed data, implements control logic based on predefined conditions and activates/deactivates the irrigation system based on soil moisture, soil temperature and humidity levels. The feedback mechanism ensures continuous monitoring and adjustment of irrigation.

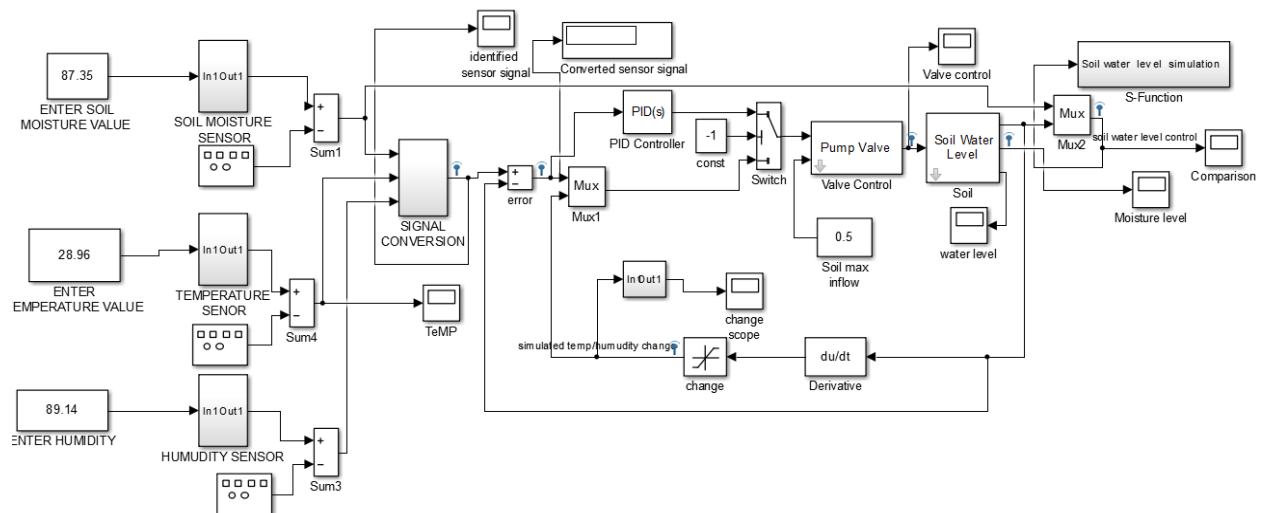


Figure 8: Simulink model of conventional irrigation system

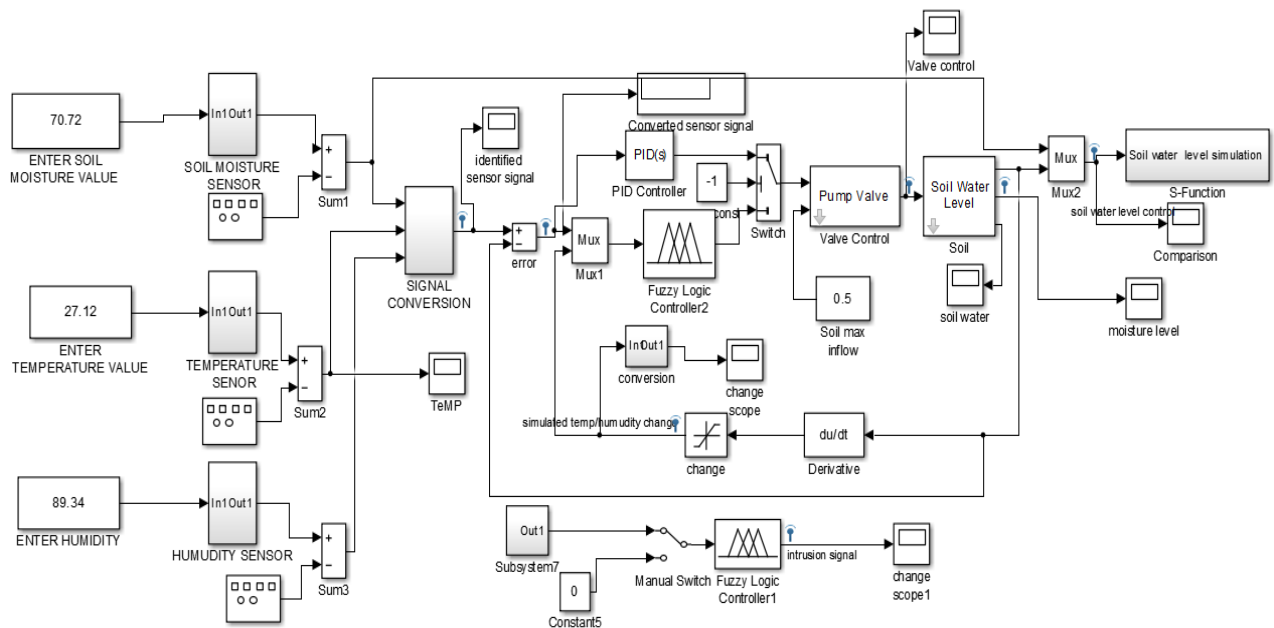


Figure 9: Simulink model of smart drip irrigation system

The smart irrigation system uses the fuzzy logic controller principles to control the valve that passes water into the soil depending on the sensor inputs. The smart drip irrigation system consists of three sensors with a feedback response enabling it to determine the level of soil water level control. The sensors include the soil moisture level, temperature and humidity. Simulink blocks were used to represent soil moisture, soil temperature and humidity inputs. These sensors were implemented using signal generators. A proportional integral derivative (PID) controller was connected alongside the fuzzy logic controller to control or regulate the amount of water that flows into the soil using a solenoid valve. The fuzzy logic controller was used to create a decision-making logic (if-then-else). The output of the controller was connected to the actuator block (solenoid valve). Once the controller receives data, it triggers actuator (valve) to start irrigation based on conditions (for example, if soil moisture is less than threshold, open valve). The inflow and outflow dynamics can be modeled in Equation 2 as:

$$U = \text{Input flow } (I_f) - \text{Output flow } (O_f) \quad (2)$$

where U is the input variable

The output flow of the soil level is given in Equation 3 as:

$$\text{Output flow } (O_f) = A_o \frac{\sqrt{2gh}}{A_s} x V_s \quad (3)$$

where A_s is the area of the soil given in Equation 4 as:

$$A_s = U_2(U_1 + U_2) \quad (4)$$

V_s is the volume of the water in the soil given in Equation 5 as:

$$V_s = \int U_2(U_1 + U_2) x (U_1 + U_2) dt (m^3) \quad (5)$$

h is the depth of the soil, g is the gravity and A_o is the system gain.

The PID controller can be modeled using Equation 6 as

$$u(t) = k_p e(t) + k_i \int e(t) dt + k_d \frac{de(t)}{dt} \quad (6)$$

where $e(t)$ is the error (difference between desired and measured soil moisture), k_p (proportional gain) increase system response speed, k_i (integral gain) eliminates steady state error and k_d (derivative gain) reduces overshoot and improves stability.

Equation 6 can be also be modeled as:

$$U(s) = P + I \frac{1}{s} + D \frac{N}{1+N\frac{1}{s}} \quad (7)$$

where N is filter coefficient

3. RESULTS AND DISCUSSION

The graph of the variation of average soil moisture content (%) with time (s) for two irrigation systems; smart drip irrigation and conventional irrigation, relative to a reference moisture level is shown in Figure 10. It is seen that the smart drip irrigation system showed a smooth and gradual increase in soil moisture, stabilizing close to the reference value with minimal fluctuations. This indicated effective feedback control, low overshoot, and good moisture regulation, ensuring efficient water use and preventing over-irrigation. In contrast, the conventional irrigation system exhibited rapid increases, repeated overshoots, and significant oscillations above the reference level, indicating poor regulation and excessive water application. During the moisture depletion phase (around 35–65 s), both systems showed a decline in moisture content, but the smart drip irrigation system responded in a more stable and controlled manner, while the conventional system continues to fluctuate. In the second cycle, the smart drip irrigation system again tracked the reference value accurately with minimal oscillation, demonstrating repeatability and steady-state stability, whereas the conventional system continued to overshoot and fluctuate.

These results agreed with previous studies by Kim et al. (2008), Ning et al. (2013), and Abioye et al. (2020), which reported that sensor-based and automated irrigation systems maintained soil moisture closer to the desired set-point with reduced fluctuations and improved water-use efficiency compared to conventional irrigation methods. Overall, the graph confirmed that smart drip irrigation provided better moisture control, improved stability, and higher water-use efficiency than conventional irrigation, making it more suitable for precision agriculture.

The graph of the average valve control error response versus time for the smart drip irrigation system and the conventional irrigation system is shown in Figure 11. Valve control error indicates the deviation between the required valve opening and the actual valve response; hence, lower and more stable values indicate better control performance.

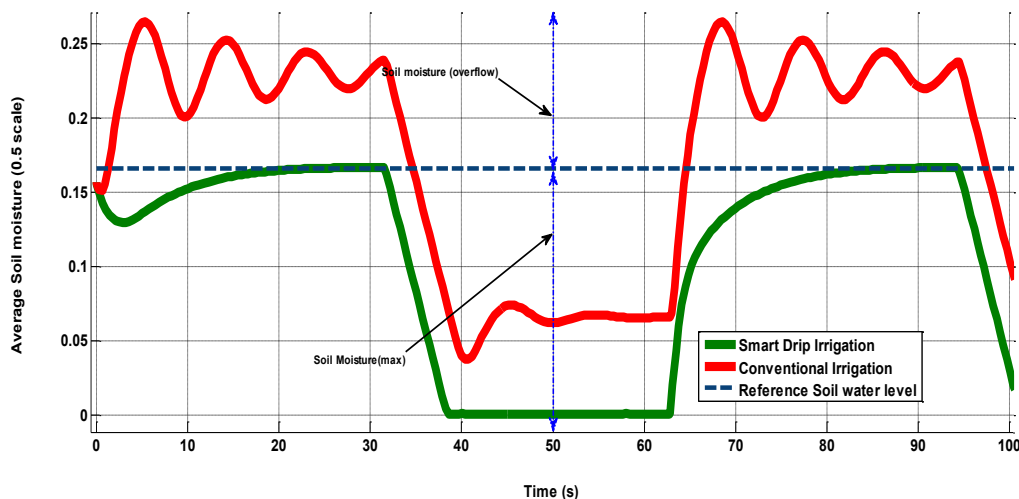


Figure 10: Graph of average soil moisture against time

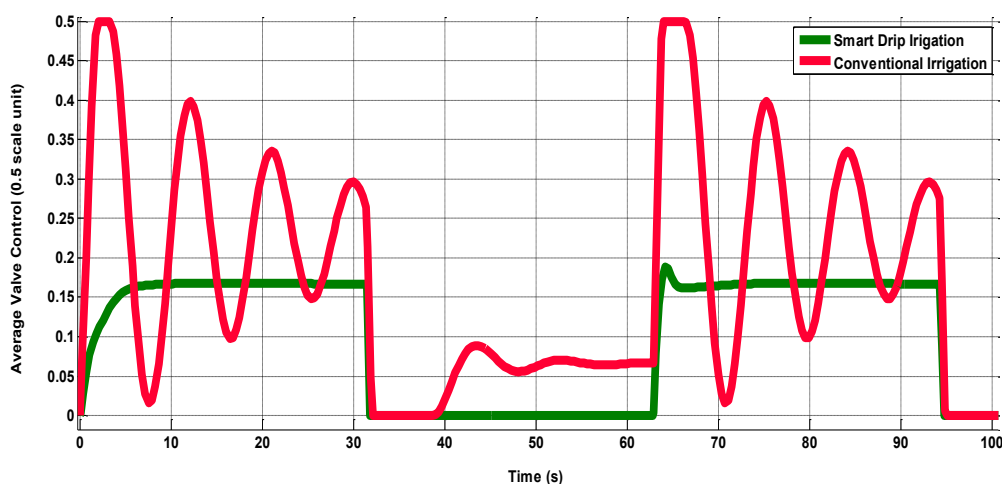


Figure 11: Graph of average water control against time

It is observed that the smart drip irrigation system demonstrated a more stable and controlled response throughout the operating period. At the initial stage (0–30 s), the smart drip system gradually rises and stabilizes at about 0.15–0.17 units with minimal fluctuations, indicating effective control action. In contrast, the conventional irrigation system exhibited large oscillations with high peaks approaching 0.5 units, showing poor stability and excessive valve fluctuations.

At approximately 35–60 s, both systems experienced a disturbance or set-point change, causing the valve control error to reduce close to zero. However, the smart drip irrigation system maintained a nearly steady response with negligible oscillation, while the conventional irrigation system still showed noticeable fluctuations before settling. Around 65 s, another disturbance occurred, and the conventional irrigation system again exhibited a sharp overshoot followed by sustained oscillations, whereas the smart drip irrigation system showed only a slight transient increase and quickly returned to steady-state operation. At the final stage (95–100 s), both responses dropped toward zero, but the smart drip system maintained smoother behaviour.

These results indicated that the smart drip irrigation system provided better valve control accuracy, lower overshoot, and improved damping characteristics compared to the conventional irrigation system.

The reduced oscillatory behaviour implied more precise water flow regulation and efficient control performance.

Compared with previous studies such as Bowlekar et al. (2019) and Abioye et al. (2020), which reported improved irrigation control but still observed moderate fluctuations during transient conditions, the major difference in the present study is the significantly lower valve control error and near elimination of sustained oscillations after disturbances. Thus, the developed smart drip irrigation system has superior controller tuning and better disturbance rejection, resulting in more stable and precise irrigation control than those previously reported. The graph of supply flow error response (in m^3/s) versus time (in seconds) for the smart drip irrigation system and the conventional irrigation system is shown in Figure 12.

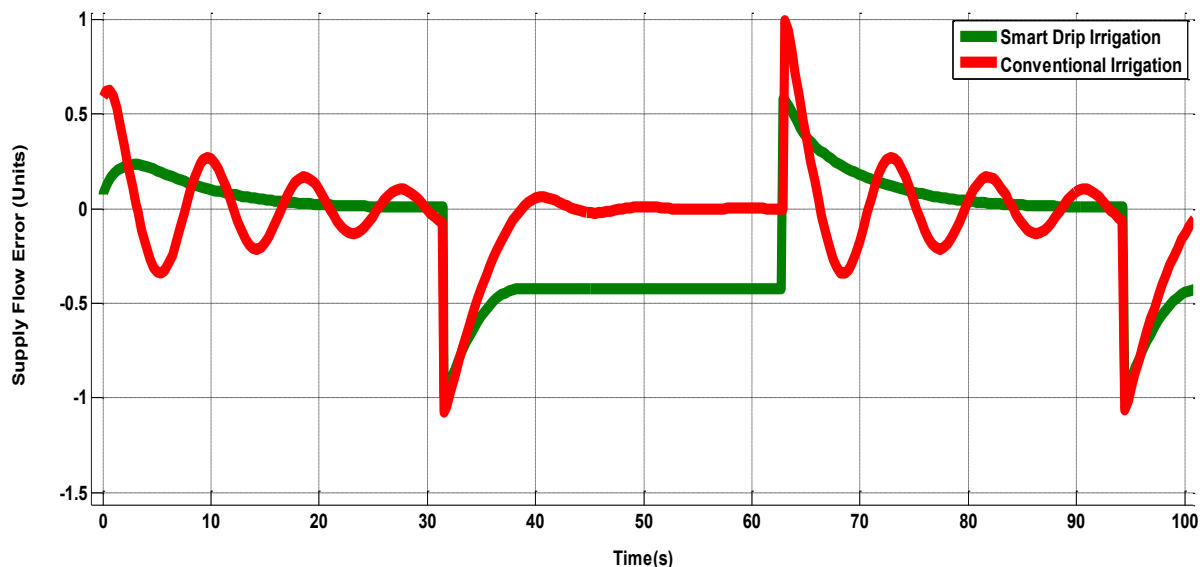


Figure 12: Graph of supply flow error against time

Supply flow error refers to the deviation between the expected water flow rate and the actual water flow rate delivered to the crops. It is observed that the CIS produced significant fluctuations and spikes over time while SDIS remained relatively stable with fewer and smaller fluctuations. There were sharp deviations, especially around 30 seconds and 60 seconds, indicating instability in water flow regulation. These deviations were caused by environmental variations (changes in temperature or soil conditions). Around 30 seconds mark, while the CIS dropped sharply, the SDIS maintained a steady flow indicating better control. At around 60 seconds, the CIS exhibited a large spike due to inconsistent water supply while SDIS affected slightly, quickly returned to stability reinforcing its efficiency. The stability of the SDIS was due to the incorporation of FLC ensuring optimal water distribution.

Compared with previous studies such as Abioye et al. (2020) and Bowlekar et al. (2019), which reported improved performance of automated irrigation systems but still observed moderate transient oscillations, the major difference in the present study is the significantly reduced oscillatory behaviour and faster recovery to steady-state conditions. This implies that the smart drip irrigation system developed in this study has better controller tuning and superior disturbance rejection, leading to more precise and efficient irrigation performance than those previously reported. Thus, the SDIS is more efficient over the CIS in maintaining consistent water flow leading to water conservation and better crop management.

The graph of soil moisture feedback error response versus time for the smart drip irrigation system and the conventional irrigation system is shown in Figure 13. Soil moisture feedback error represents the

deviation between the desired soil moisture level and the actual measured moisture; values closer to zero indicate better control accuracy.

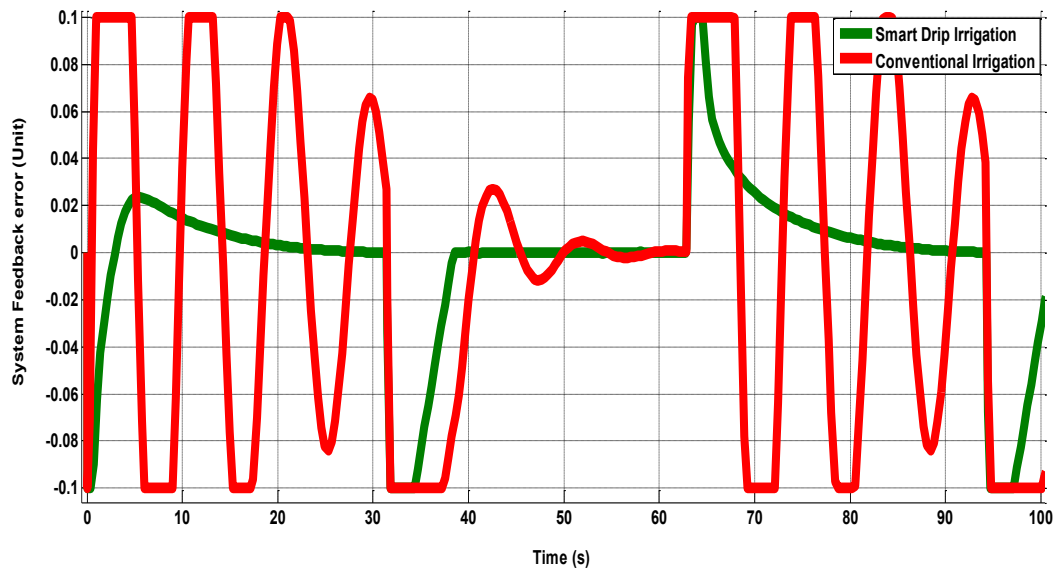


Figure 13: Graph of system feedback error against time

It is seen that the smart drip irrigation system showed a smoother and more stable response throughout the operating period. At the initial stage (0–30 s), the smart drip system rises gradually and then decayed smoothly toward equilibrium with reduced fluctuations. In contrast, the conventional irrigation system exhibited repeated sharp oscillations between positive and negative peaks, indicating unstable moisture regulation and excessive corrective action.

At approximately 35–60 s, both systems experienced a disturbance, but the smart drip system quickly stabilized near the reference point with minimal oscillation, whereas the conventional irrigation system continued to fluctuate before settling. Around 65 s, another disturbance caused a sudden increase in error; however, the smart drip irrigation system showed a controlled transient response and gradually returns toward zero, while the conventional irrigation system again exhibited large sustained oscillations throughout the remaining period. Towards the final stage (95–100 s), the smart drip system still showed smoother recovery compared to the abrupt fluctuations in the conventional system.

This result indicated that the smart drip irrigation system provided better soil moisture regulation, lower oscillatory behaviour, and improved stability compared to the conventional irrigation system. This implied more accurate moisture sensing and water application, reducing the risk of over-irrigation or under-irrigation.

Compared with previous studies such as Bowlekar et al. (2019) and Abioye et al. (2020), which reported improved moisture control in automated irrigation systems but still observed moderate transient oscillations, the major difference in this study is the smoother error decay and significantly reduced oscillations after disturbances. Thus, the developed smart drip irrigation system achieved better feedback control accuracy and superior disturbance rejection, resulting in more precise soil moisture regulation than previously reported.

4. CONCLUSION

The design, simulation and fuzzy logic control of a smart drip irrigation system for enhanced water use efficiency and crop productivity demonstrated the potential of integrating automatic control mechanisms to optimize water usage, improve crop yield and reduce operational costs. By leveraging

sensors, microcontrollers and real-time data analysis, the smart drip irrigation system ensures efficient water distribution based on soil moisture level, thereby minimizing waste and promoting sustainability. Simulation results confirmed the effectiveness of the smart drip irrigation system in conserving water while maintaining optimal crop health.

It is recommended that future works should focus on enhancing system scalability, incorporating artificial intelligence (AI)-driven decision making and integrating renewable energy sources to further improve efficiency and environmental impact. This smart irrigation approach paves the way for more resilient and resource-efficient agricultural practices.

5. ACKNOWLEDGMENT

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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