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Fuzzy Logic and IoT-Based Smart Irrigation System †

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Abstract: Conventional irrigation methods frequently generate excessive or inadequate watering, resulting in the wastage of water and energy and diminished agricultural yields. This study presents a novel intelligent irrigation system that incorporates fuzzy logic and the Internet of Things (IoT) to automate the control of water pumps, thereby eliminating the requirement for human interaction. This novel method enables users to effectively preserve water and electricity by mitigating the issues of excessive and insufficient irrigation of crops. The system utilizes climate sensors that are combined with electrical circuits and connected to an Arduino and a fuzzy inference system (FIS) model to consider climate conditions and soil moisture levels. The sensors are responsible for collecting data utilized by the FIS model to control the speed of the water pump effectively. The FIS model integrates fuzzy logic to analyze the data obtained by the Arduino. This analysis enables the Arduino to adjust the pump speed by considering a wide range of sensor inputs. The implementation of this autonomous system eliminates the requirement for human intervention and enhances agricultural productivity by accurately dispensing the optimal quantity of water at the proper intervals. The cessation of water supply occurs when the soil moisture levels reach a sufficient state and resume when the moisture levels fall below predetermined limits regulated by various environmental circumstances. A comparative analysis examines the suggested technology, drip irrigation, and manual flooding. The comparison results demonstrate that the intelligent irrigation system accomplishes water and energy conservation.

Keywords: fuzzy inference system; fuzzy logic; Internet of Things; sensors; smart irrigation

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1. Introduction

Agriculture plays a prominent role in the economy, and people recognize it as a vital cornerstone of the economic frameworks of developing nations. For several decades, there has been a close association between it and the growth of vital food crops [1]. The "Global Water Crisis" predicts that the increasing demand for clean water amid drought and hot weather conditions would seriously affect agriculture [2]. The presence of water shortage in both agricultural and non-agricultural communities will significantly influence the quality of life for residents, particularly those who depend on these towns for food production on an intermittent basis [3]. When aiming to get a prosperous crop yield, it is vital to consider both the irrigation methodology employed and the volume of water consumed. It is imperative to ensure that the quantity of water provided aligns precisely with the specific requirements of the plants, hence preventing any surplus [4].

Approximately 70% of the Earth's freshwater resources are allocated for agricultural and food production, making it the primary consumer of water globally [2,5]. Considering the substantial water consumption within the industrial sector, it is reasonable to expect a surplus allocation of water resources towards agricultural activities. Experts have identified low irrigation efficiency as a significant contributor to water wastage [6,7].

The United Nations Food and Agriculture Organization asserts that runoff and evapotranspiration cause the wastage of approximately 60% of the water used for irrigation. [8]. Digital advancements in agriculture are crucial, not just in less developed nations grappling with food and water scarcity but also in affluent nations due to climatic fluctuations, antiquated and ineffective irrigation systems, pandemics, and other unanticipated obstacles [4,9]. The implementation of automated agricultural irrigation systems provides farmers with the capacity to regulate water volumes accurately, regardless of the availability of labour for manual valve management and plant growth monitoring [10]. In the present era, automation has been widely implemented in various sectors, encompassing industries, household administration, and agriculture [11]. Using sensor-driven irrigation systems deployed throughout agricultural fields offers a promising option for managing irrigation maximizing crop productivity while promoting water conservation. Intelligent agricultural systems provide a sophisticated technology that enables farmers to improve crop output through cost-effective techniques [12].

The efficiency of intelligent irrigation systems utilizing IoT technology and fuzzy logic controller (FLC) can be enhanced by evaluating data and implementing irrigation adjustments based on factors such as soil moisture and temperature [13]. Communication technologies such as Zigbee, LoRaWAN, and cloud computing facilitate monitoring and storing data in real-time [14]. The Internet of Things (IoT) employs diverse networks to gather data from the physical environment, employing optimization techniques to enhance operational efficiency. The abundance of applications provides evidence for the adaptability of fuzzy logic, a computational approach that effectively manages uncertainty and efficiently makes decisions in practical contexts [15].

Researchers have conducted a plethora of studies on utilizing fuzzy inference systems and Internet of Things (IoT) technologies in agriculture [16]. In their research, the authors in reference [17] provide a methodology for identifying meteorological condition variables and utilizing this data to quantify the frequency and quantity of water required for cultivation. The proposed system design [18] examines a fog wireless communication platform for monitoring and managing sensors and actuators, intending to determine the irrigation requirements for crops. Previous research [19] shows that implementing a decision support system can enhance regulated irrigation practices, ensuring consistent soil moisture levels. Additionally, such a system can prioritize areas with low water content while minimizing the negative impacts of irrigation on regions with high water content. In the study conducted by the authors [20], novel irrigation techniques were devised to optimize agricultural water utilization through fuzzy logic. The researchers employed a Mamdani control system and utilized MATLAB and Simulink software to conduct simulations. The results exhibited accurate modelling and underscored the efficacy of the Mamdani fuzzy logic control system in optimizing the utilization of water resources in agriculture. In reference [21], fuzzy logic systems are employed to improve decision-making assessments instead of standard acknowledgement control procedures. Fuzzy logic can enhance the adaptive capabilities of irrigation systems in response to the ever-changing dynamics of their surrounding environment. The manipulation of if-then rules in fuzzy inference systems can be efficiently achieved by applying fuzzy logic and set theory [22]. This article employs the widely adopted and accessible Mamdani methodology for irrigation control. This approach exhibits similarities to human cognition and linguistic processes.

This article explores implementing an intelligent irrigation system based on fuzzy logic. This technology calculates the optimal irrigation volume for crops by considering meteorological conditions. The attainment of an ideal crop yield is contingent upon providing an appropriate quantity of water avoiding excessive and inadequate amounts. The created fuzzy control system integrates four input parameters: soil moisture, solar radiation, air temperature, and air humidity. We have considered these specific components because they influence water evaporation from the soil. The management of the pump's speed influences the rate of water delivery, achieved through the regulation of the output parameter of the fuzzy logic control system. This invention differentiates itself from prior methodologies by using a more extensive set of input variables and formulating a direct fuzzy rule based on the interconnectedness between each input and output parameter. The system aimed to enhance farmers' engagement and facilitate their transition to intelligent agriculture practices. The main contributions of this study can be summarized as follows:

- This study focuses on designing and implementing an intelligent irrigation system that utilizes fuzzy logic and leverages the Internet of Things (IoT) for real-time capture of meteorological and soil information. The system aims to enable informed irrigation decisions by applying a fuzzy inference system.
- The motor's activation or deactivation is automated based on the data obtained from the soil moisture sensor in order to mitigate excessive consumption of water and electricity.
- The engine is automatically deactivated in reaction to rain to conserve electricity resources.
- There is no need for human intervention.

The remaining document sections are structured as follows: Section 2 explains the technique utilized in developing our work. Section 3 presents the outcomes achieved following the system's implementation, discussions, unresolved issues, and a comparison against other cited systems. Concluding the paper, Section 4 underscores the key takeaways of the research and outlines potential paths for future investigations.

2. Proposed System Model

By utilizing real-time data collected from sensors, an intelligent irrigation system enhances the efficacy of watering practices. The depicted system architecture, as illustrated in Figure 1, showcases the process flow. In this arrangement, data is collected by sensors, afterwards interpreted by an Arduino, and ultimately utilized by the fuzzy controller to determine the optimal timing for grass irrigation. Integrating the Internet of Things (IoT) and Wireless Sensor Network (WSN) technology enables smooth communication between sensors and Arduino devices, facilitating efficient information exchange.

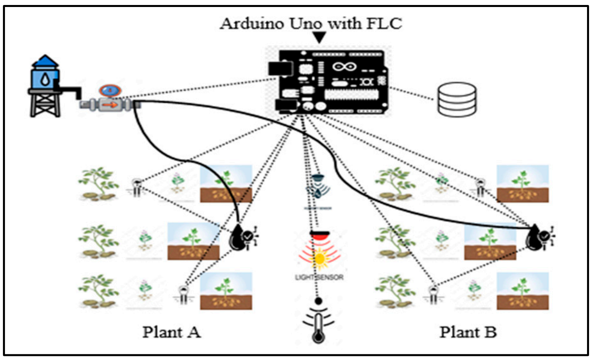

Figure 1. Proposed architecture of Smart Irrigation System.

2.1. Sensors and Communications Media

The current study employed five sensors to monitor various environmental variables. We used the DHT11 sensor to measure humidity and temperature, the REES52 sensor to assess soil moisture, and the LM 393 sensor to analyze sun radiation. We employed a flow sensor to quantify the water flow rate to regulate irrigation. ZigBee technology facilitated enhanced communication among system components while the microcontroller effectively processed sensor data.

2.2. Fuzzy Inference System for Precision Agriculture

The fuzzy controllers utilized Mamdani's fuzzy inference method in the present investigation. Figure 2 depicts the internal structure of the fuzzy inference system used for a water pump. The initial step of the fuzzy logic controller (FLC) involves acquiring data from sensors responsible for measuring a range of environmental characteristics, including temperature, humidity, sunshine intensity, and soil moisture.

We compute fuzzification rules by utilizing sensor data. The soil moisture sensor facilitates the determination of watering requirements. We initiate irrigation when the relative humidity drops below 17%. Fuzzy logic determines the length of irrigation in FLC. The rule-based approach determines the optimal frequency and duration of irrigation. The proposed Fuzzy Logic Controller (FLC) utilized triangle and trapezoidal functions as piecewise linear membership functions to conduct the fuzzification process. The method for constructing a μ_{triangle} is shown in (1) below:

$$\mu_{triangle}(x; a, b, c) = \begin{cases} 0, & x \le a \\ \frac{x-a}{b-a}, & a \le x \le b \\ \frac{c-x}{c-b}, & b \le x \le c \\ 0, & c \le x \end{cases} \tag{1}$$

$$\mu_{trapezoidal}(x; a, b, c) = \begin{cases} 0, & x \le a \\ \dfrac{x-a}{b-a}, & a \le x \le b \\ 1, & b \le x \le c \\ \dfrac{d-x}{d-c}, & c \le x \le d \\ 0, & d \le x \end{cases} \tag{2}$$

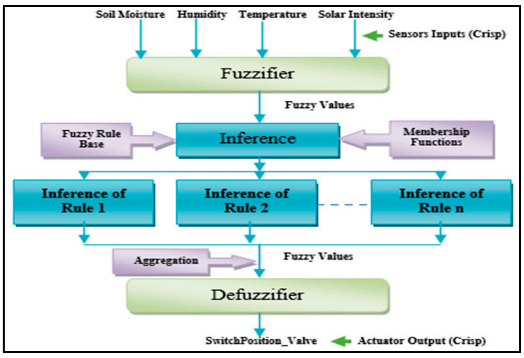

Figure 2. Internal structure of fuzzy logic controller.

Tables 1–5 present the threshold values for the inputs and output. As mentioned earlier, the values play a critical role in the generation of rules through the utilization of membership functions in the fuzzification process. These reference points serve as a basis for identifying the appropriate linguistic phrases and fuzzy sets linked to each variable.

Table 1. Soil Moisture Threshold factor.

Soil Moisture Reading (%)	Category
0–17	Dry
18–50	Normal (Ideal)
51–100	Wet

Table 2. Solar radiation Threshold factor.

Solar Radiation Reading (%)	Category
0–4	Dark
5–50	Medium
51–100	Light

Table 3. Humidity Threshold factor.

Humidity Reading (%)	Category
0–49	Low
50–84	Medium (Ideal)
85–100	High

Table 4. Temperature Threshold factor.

Temperature Reading (°C)	Category
0–16	Cold
17–22	Warm (Ideal)
23–45	Hot

Table 5. Irrigation Duration Threshold factor.

Irrigation Duration (Min)	Category
0–2	Very Short
3–5	Short
6–12	Medium
13–25	Long
26–45	Very Long

The system included fuzzy logic principles by formulating and exploiting the membership functions described in (1) and (2). The fuzzy logic controller (FLC) would require 81 rules to decide the irrigation choice, considering four inputs with three membership functions each. However, employing careful examination, the established principles were refined to 49, resulting in optimization. Table 6 presents a compilation of exemplary firing rules.

Table 6. Fuzzy rules for proposed system.

1	If (Soil_Moisture is Normal) and (Humidity is Low) and (Air_Temperature is Cold) and (Solar_Radiation is Light) then (SwitchPosition_Valve is S) (1)
2	If (Soil_Moisture is Dry) and (Humidity is Low) and (Air_Temperature is Cold) and (Solar_Radiation is Light) then (SwitchPosition_Valve is M) (1)
.	…..
49	If (Soil_Moisture is Normal) and (Humidity is High) and (Air_Temperature is Hot) and (Solar_Radiation is Medium) then (SwitchPosition_Valve is S) (1)

Additionally, the MIN-MAX inference aggregation method and criteria were employed to ascertain the stress levels. We used the highest value to modify the output fuzzy region while employing the minimal value of the predicate truth to restrict the fuzzy union. Employing the minor operator diminished the overall level of certainty of the stress state. Utilizing the MAX composition technique established the membership function for irrigation time. The intelligent irrigation system uses four inputs, namely moisture (M), temperature (T), humidity (H), and light (L). We use Equations (3) and (4) to compute the MIN-MAX aggregation inference.

$$M \cup T \cup H \cup L = \{x, \min\,(mM(x), mT(x), mH(x), mL(x))|x \in X\} \tag{3}$$

$$M \cap T \cap H \cap L = \{x, \max\,(mM(x), mT(x), mH(x), mL(x))|x \in X\} \tag{4}$$

The final stage in the intelligent irrigation system is the process of defuzzification, which entails converting the fuzzy output into a numerical value. The centroid defuzzification technique, as depicted in (5), is employed to ensure precise outcomes.

$$x^* = \frac{\int \mu_i(x).xdx}{\int \mu_i(x).dx} \tag{5}$$

$$Y_1 = \frac{(Y_{VS}C'_1 + Y_S C'_2 + Y_M C'_3 + Y_L C'_4 + Y_{VL} C'_5)}{(C'_1 + C'_2 + C'_3 + C'_4 + C'_5)} \tag{6}$$

Equation (5) illustrates the process of generating the de-fuzzified output, denoted as x*, for the output variable x using the membership function $\mu_i(x)$. On the other hand, (6) is employed to determine the Centroid of Area (CoA) for the proposed system. In this equation, (Y) represents the centroid of the output variable, while C'_1, C'_2, C'_3, C'_4 and C'_5 correspond to the results of the membership functions. Additionally, Y_{VS} = {VS_t = 2}, Y_S = {S_t = 5}, Y_M = {M_t = 12}, Y_L = {L_t = 25}, Y_{VL} = {VL_t = 45} are the singleton functions associated with each output.

3. Results and Analysis

The work involved the development of a fuzzy inference system utilizing Mamdani-type fuzzy logic for the exact control of the irrigation switch position. The switch position, ranging from 1 to 5, was established based on four inputs: soil moisture, temperature, humidity, and light intensity. A numerical value of 1 signifies a reduced frequency and timing of water flow, whilst several 5 denotes the presence of a continuous and unrestricted water flow. We implemented the fuzzy inference system using the MATLAB software. Figures 3 and 4 exhibit the results obtained for water flow control, presenting the outcomes in diverse formats.

Upon examination of Figure 3, it becomes apparent that several environmental factors have a significant role in influencing the determination of the water valve's switch position and the irrigation duration. When we measure the soil moisture level at a low percentage of 9.69%, along with a relative humidity of 44.7%, an ambient temperature of 31.4 °C, and moderate sun radiation of 609 lux, we recommend adjusting the switch position to the extended position, which is the fourth position. The provided data suggests that the water flow will persist for an estimated duration of 14.4 min in order to facilitate the irrigation of the plants.

Likewise, Figure 4 illustrates an additional scenario whereby the soil moisture content is within a standard range of 43.5%, representing an optimal condition for the growth of potato plants. The relative humidity is at a moderate level, measuring 82.7%. The air temperature reads 13.7 °C, characterizing it as cold. Moreover, we observe negligible sun radiation. In this instance, the obtained output demonstrates a significantly diminished water flow value (4.91), implying that the switch position is close to the lower threshold. That adheres to the precise guidelines for this problem, as the predicted result in such situations will likely be extremely minor.

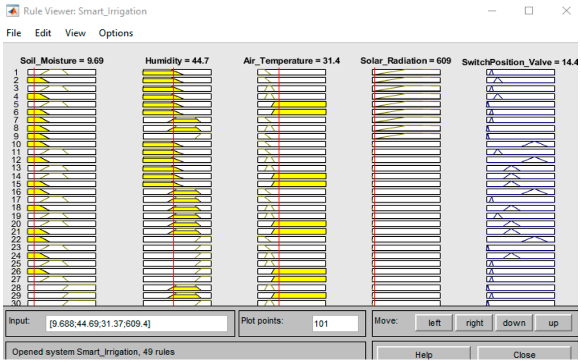

Figure 3. Switch position (Long).

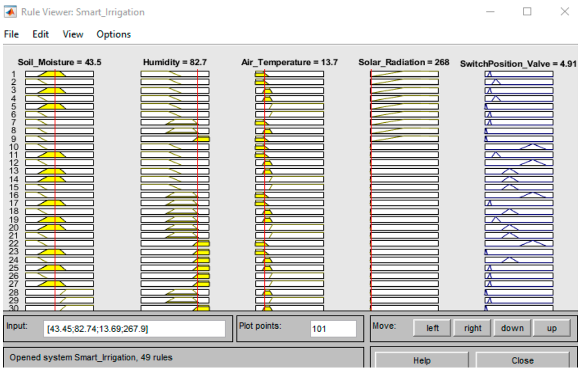

Figure 4. Switch position (Short).

Moreover, Figure 5 illustrates the correlation between the two independent variables, namely humidity and soil moisture, and the dependent variable, which is the switch position of the solenoid valve. The figure appears as a surface plot generated using MATLAB. The figure demonstrates that in instances where moisture levels are low, resulting in a yellow colouration on the plot, there is a notable increase in the water flow through the system. In contrast, when moisture levels are elevated, as denoted by a blue hue on the graph, the magnitude of water flow is modest. The presented graphic illustrates the inverse correlation between moisture levels and water flow.

Similarly, Figure 6 illustrates the correlation between elevated temperatures and augmented evapotranspiration, hence requiring a larger quantity of water for irrigation.

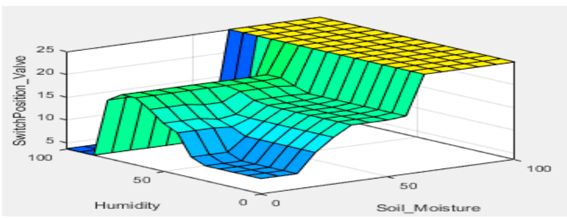

Figure 5. Relationship among humidity, soil moisture and corresponding output for the FLC.

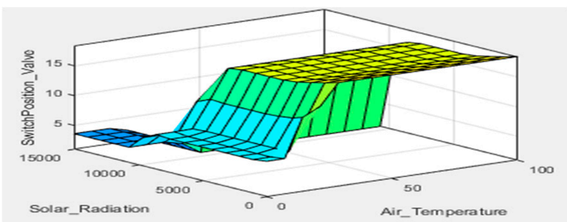

Figure 6. Relationship among temperature, solar radiation and corresponding output for the FLC.

In order to provide empirical support for the conclusions drawn by the proposed system, a comparative evaluation is undertaken to compare its performance with that of the most recent systems [23,24]. These systems were selected as benchmarks based on their resemblance to the proposed irrigation approach. The evaluation process-maintained consistency in the proposed system's conditions, features, periods and existing solutions to guarantee a comprehensive and unbiased assessment. This approach facilitated a realistic and meaningful comparison between the two.

Table 7 presents a comparative analysis of the proposed and existing models, focusing on three key parameters: weekly water volumes, actuator time, and energy consumption. The results indicate that the proposed model has a lower water use than alternative models, including those referenced in [23,24]. The reduced duration of pumping in the proposed system leads to decreased actuator operation time and diminished energy consumption. Significantly, the proposed model demonstrates an 11% reduction in energy use compared to the previous model. In Figure 7, a comparison is presented between the intelligent irrigation system that has been proposed and existing systems in terms of their water and energy consumption during four months. The chosen time frame has been determined based on its congruence with the ideal duration necessary for the growth and development of potato plants.

Table 7. Proposed system evaluation.

Irrigation Models	Water Consumption (L)	Operating time of Actuators	Energy Consumption (Wh)
[23]	59	1 h 17 m 08 s	108
[24]	45	0 h 56 m 45 s	73

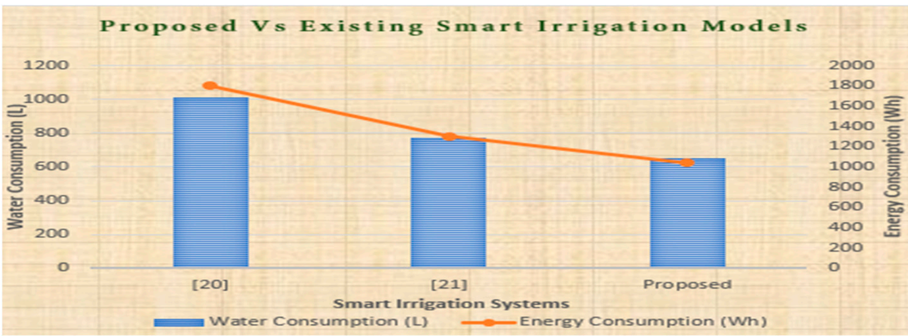

Figure 7. Comparison of proposed vs. existing smart irrigation systems.

The data presented in Figure 7 demonstrates the significant reduction in water consumption achieved by the suggested system. Specifically, it indicates a decrease of 360 litres (equivalent to 45%) compared to the approach described in reference [23], and a reduction of 121 litres (equivalent to 19%) compared to the method outlined in reference [24]. Additionally, it illustrates a decrease of 760 Wh and 260 Wh in energy consumption during the potato growth phase. That emphasizes the potential advantages of adopting the proposed methodology, which incorporates smart irrigation using a fuzzy inference system and the Internet of Things (IoT). That leads to significant cost reductions for farmers regarding water, energy, and labour expenditures.

4. Conclusions

This article introduces a methodology for creating an intelligent irrigation system that tackles the difficulties posed by limited water resources in areas characterized by significant water limitations. The utilization of fuzzy inference systems and Internet of Things (IoT) technologies is employed by the system in order to facilitate the promotion of practical water usage and the enhancement of irrigation control. The fuzzy inference system, employing the Mamdani fuzzification method, effectively ascertains the ideal irrigation frequency and duration for potato cultivation. The system utilizes trapezoidal output membership functions and triangle input membership functions. The fuzzy control mechanism effectively preserves water and energy resources by regulating excessive runoff and ensuring that soil moisture remains above a predetermined threshold through gradual adjustments. Additionally, the system compensates for the loss of water resulting from evapotranspiration throughout the winter season, a period characterized by frequent excessive irrigation. Significantly, the suggested methodology retains its user-friendly nature and economic viability, even when implemented across extensive agricultural landscapes. Potential areas for future research involve investigating the incorporation of intelligent farming technology based on artificial neural networks (ANNs). This integration can assist farmers and producers in reducing waste and improving productivity in multiple domains. For instance, it could optimize fertilizer use and enhance crop output.

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