engineering proceedings

Proceeding Paper

Fuzzy Logic Based Sprinkler Controller for Precision Irrigation System: A Case Study of Semi-Arid Region in India †

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† Presented at The 11th International Electronic Conference on Sensors and Applications (ECSA-11), 26–28 November 2024; Available online: https://sciforum.net/event/ecsa-11.

Abstract: A sophisticated precision irrigation system to precisely determine the water requirements of crops and implement effective irrigation control strategies for automated, real-time, and targeted crop irrigation in the semi-arid regions of India. This system incorporates ZigBee Technology, Wireless Sensor Networks, and Fuzzy Logic based control methodologies. This system discussed by the author actively gathers data for the most prominent parameters of the targeted area such as soil water potential and meteorological conditions, encompassing ambient temperature, humidity, solar radiation, and wind speed. This data obtained from the sensors then processed with the fuzzy logic based algorithms gets utilized to transmit precise irrigation control instructions to the system. Moreover, this proposed system employs the Priestley and Taylor Model (PTM) so as to calculate farmland evapotranspiration (ET). This algorithm has been chosen instead of Penman & Monteith Model (PMM) because of its better accuracy and simple calculations. Both field evapotranspiration and soil water potential serve as crucial inputs for the suggested fuzzy controller based system. A comprehensive multi-factor control rule library is establish, facilitating the implementation of fuzzy-control mechanisms for regulating crop irrigation water requirements with enhanced performance. The testing results obtained from this proposed system demonstrate the system's economic viability and practicality, underscoring its reliability in communication, high control accuracy, and suitability for precision irrigation in semi-arid regions in India that in turn enhances the crop yield.

Keywords: precision irrigation; wireless sensor network; fuzzy controller; ZigBee; semi-arid regions

Citation: Prasad, R.; Srivastava, A.K.; Tiwari, R. Fuzzy Logic Based Sprinkler Controller for Precision Irrigation System: A Case Study of Semi-Arid Region in India. *Eng. Proc.* **2024**, *6*, x. https://doi.org/10.3390/xxxxx

Academic Editor:

Published: date: 26 November 2024

1. Introduction

The agricultural water resource utilization in semi-arid regions of India currently grapples with a dual challenge of low efficiency and simultaneous wastage, posing a significant hurdle to the progress of irrigated agriculture [1]. Compounding this issue is the prevalence of drought, a prominent environmental stressor during crop-growing seasons in the country. The impact of drought-induced water deficits on crop growth, development, and yield surpasses that of all other stresses combined, as indicated by various studies [2–4]. Maintaining specific soil moisture content becomes paramount for ensuring crop survival, with optimal moisture levels resulting in increased biomass. Conversely, excessively high soil moisture content can lead to root rot and excessive nutrient leaching, damaging the soil [5]. Fewer pollution is contributing to the agricultural water resource challenge [6]. Addressing these complex issues necessitates the adoption of precision irrigation as a fundamental solution [7].

Precision irrigation involves use of precipitation and soil water while efficiently managing irrigation water [8,9]. It entails precise control over the timing and location of irrigation to align with the crop's water requirements, thereby optimizing economic, social, and ecological benefits in agricultural production. Successful implementation of precision irrigation hinges on meeting specific conditions:

1. Calculate accurate crop water demand.
2. Successfully use of advanced and low-cost technology to maximize the yields.
3. Precise irrigation control make appropriate management decisions.

Information pertaining to crop water demand encompasses a comprehensive array of data, including soil details, crop specifications, and environmental factors [10]. Multitude of sensor is deployed to gather relevant information, as highlighted in recent studies [11–14]. These sensors cover a spectrum of detection parameters such as soil moisture content, soil temperature, soil water potential, crop transpiration, leaf moisture, ambient temperature, ambient humidity, solar radiation, and more. Advancements in technology have led to the maturation of measurement techniques and equipment for crop moisture information. It includes systems based on acoustic emission signals linked to plant diameter deterioration and crop-water stress, infrared temperature techniques applied to crop canopies. Despite the progress observed in these areas, a critical evaluation of the current application status reveals notable shortcomings in the development.

In its current state, the main facets are as follows:

1. Conventional irrigation control systems predominantly operate through a wired framework, employing serial bus and field bus technology, rendering system installation and maintenance uncomplicated [15].
2. Precise irrigation, a sophisticated system, is intricately influenced by multi-sensor information derived from soil, crops, and the environment. Presently, a deficiency exists in terms of suitable control strategies. Freshly, significant strides have done for wireless sensor networks and fuzzy control technology into precision irrigation system research. This development lays a robust foundation for innovative ideas and promising applications in precision based irrigation. Notably, wireless transmission utilizing ZigBee technology in sensor networks that exhibits characteristics such as low power consumption, cost-effectiveness, expansive network range and capacity, simplicity and flexibility in the network structure. Its emphasis on low-speed transmission renders it particularly well-suited for precision irrigation applications, garnering interest from scholars both domestically and internationally areas fall under the semi-arid regions [16].

Extensive research has delved into refined irrigation systems. However, within these systems, the predominant utilization of ZigBee wireless sensor networks [17] lies in mixture of soil, crop, or environmental data, offering users valuable references for irrigation decision-making. Integrated systems that amalgamate ZigBee technology for technical information gathering and automatic irrigation whose control remain relatively scarce. Fuzzy control, a sophisticated control system, grapples with establishing precise mathematical models [18]. Addressing this challenge, Anitha N. et al. [19] suggested Nano-sensor based precision irrigation system for cultivation. Smart-irrigation system based on fuzzy controller, specifically-geared toward automatic water-saving sprinkler irrigation control [20]. Despite these advancements, existing studies predominantly leverage soil moisture information as hazy input, disregarding crucial crop and environmental data, leading to suboptimal decision-making accuracy. Clearly, there remains room for refinement in this domain. Indeed, irrigation decisions are influence by a myriad of sensors capturing comprehensive information from soil, crops, and the environment. In addressing this complexity, in [21] ingeniously-integrated soil water potential and farmland evapotranspiration as inputs, crafting a fuzzy irrigation decision-making system for precision crop control. This approach enables more holistic assessments and managerial decisions regarding water demand. However, a notable limitation lies in the current control system, grounded in wired connections, leading to elevated system costs. This economic constraint hampers the widespread adoption and application of the system in various fields.

ZigBee [22] enabled wireless sensor networks and fuzzy control individually contributes flexibility and maneuverability to precision irrigation systems. However, integration of technologies remains relatively underexplored, resulting in a scarcity of practical precision irrigation systems that leverage the combined benefits of wireless sensor networks [23] and fuzzy control. This article addresses this gap by intricately combining wireless sensor networks and fuzzy control technology in designing the structure of a comprehensive precision irrigation system. The article is divide into five section, Section 2 presents the proposed model architecture and information flow of wireless sensor network, Section 3 present the design and implementation of fuzzy controller, Section 4 present the application and verification of the outcomes of the proposed model and Section 5 presented the conclusion and future scope of the proposed model.

2. Proposed Model

2.1. Overall System Design

As illustrated in Figure 1, the system comprises crop planting areas, micro-weather stations, and base stations, collectively forming a remote monitoring center. The system's information flow is depicted in Figure 2. Within the planting area, crop soil-water potential detection sensors, irrigation pipe networks, and sprinkler irrigation heads are strategically arrange, each equipped with a fuzzy irrigation control valve. A mini weather sensing station is deploying in the remote area. It is use for capture meteorological data such as air pressure, ambient temperature, humidity, precipitation, wind speed, wind direction, and solar radiation.

The communication of soil properties and meteorological information occurs through the ZigBee wireless sensor network, transmitting data to the base station computer. The base station computer, equipped with automatic analysis capabilities, processes the received information to calculate crop irrigation water demand. Results are then transmitted back through the ZigBee wireless sensor network, regulating the opening and closing times of spray and drip irrigation valves in the crop planting area, thereby achieving automated irrigation.

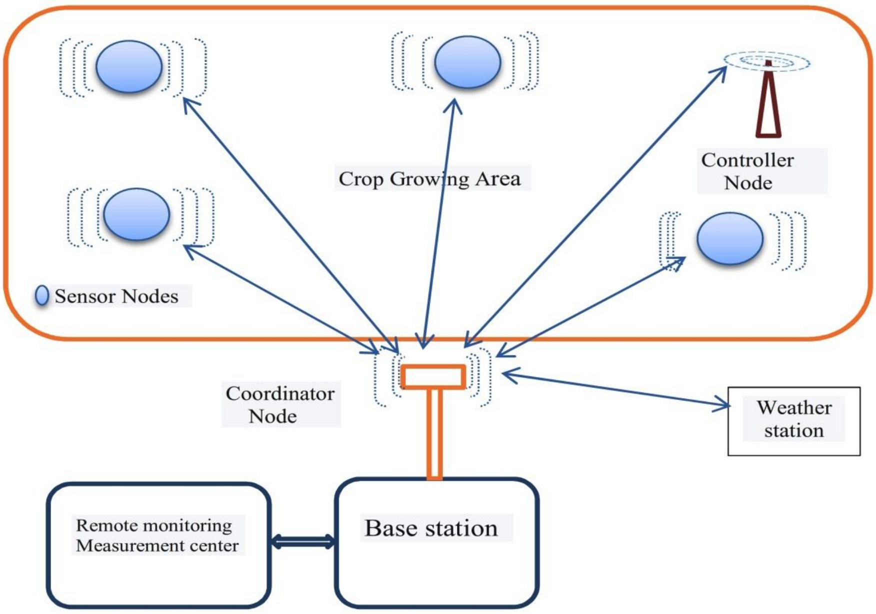

Figure 1. Architecture of wireless sensor network.

Beyond local control, the base station computer provides real-time monitoring and control process information and facilitates communication with the remote monitoring center, enabling information sharing through the Internet. This integrated system ensures a seamless and efficient flow of data and control for precision irrigation.

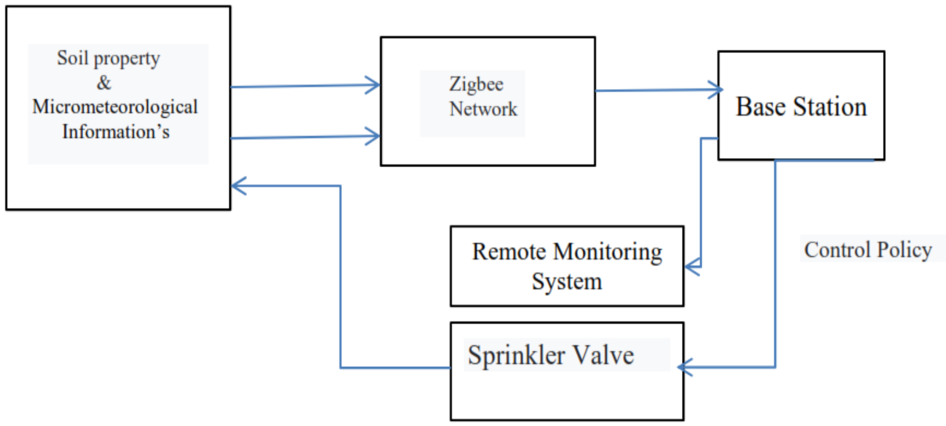

Figure 2. Information flow of WSN.

As depicted in Figure 1, the ZigBee wireless sensor network adopts a star network topology, categorizing nodes into three distinct types: sensor nodes, controller nodes, and tuner nodes. Sensor nodes, including soil water potential sensors and micro-air station sensors, are interconnected to gather and transmit essential information pertaining to soil attributes and meteorological conditions. Controller nodes, on the other hand, interface with sprinkler irrigation control valves, overseeing the operation of sprinkler and drip irrigation heads. They also regulate valve opening times using a timer mechanism and possess an interrupt response feature to manage directives received from the base station computer. The spatial arrangement of soil water potential sensor nodes and control device nodes is meticulously designed based on crop types, soil characteristics, and terrain considerations. This design is optimized to ensure reliable signal transmission. Furthermore, the layout of controller nodes takes into account the existing irrigation pipe network and sprinkler heads, aiming for a harmonious balance between irrigation effectiveness and cost efficiency.

A coordinator node is linked to the base station, managing address allocation between sensor and controller nodes while overseeing signal transmission. During system operation, the coordinator node issues a data reading command to sensor nodes every 60 min, relaying the acquired data to the base station computer via the serial port. This comprehensive arrangement ensures the seamless functioning of the system, facilitating efficient communication and data flow for precision irrigation. The system software operating on the base station computer is founded on LabVIEW's development of virtual instrument technology [24]. In this configuration, the base station computer assumes the role of the system monitoring center, tasked with the comprehensive responsibilities of wireless sensor network node information collection, node status management and monitoring, as well as the processing, decision-making, and control output related to fuzzy crop irrigation amount regulation. Leveraging LabVIEW's virtual instrument technology proves pivotal to the system's efficacy, as it not only facilitates information collection and management but also enables precise control decisions. Consequently, LabVIEW serves as a crucial and versatile platform, providing the industry with a robust foundation for the seamless operation of this intricate system.

2.2. Wireless Sensor Network Node Design

The design of wireless sensor network nodes serves as the pivotal focus within the hardware architecture. These nodes represent miniature devices endowed with information processing and communication capabilities characteristic of embedded systems. The system adopts a modular design for the nodes, wherein three types share a common core module, and each type is equipped with distinct expansion modules. Figure 3 illustrates the node configuration employing the JN5139 wireless microprocessor module as its core [25]. This core integrates the ZigBee wireless transmission unit, featuring an integrated power enhancement function, as well as a serial communication interface, sensor interface, digital output interface, and power supply interface, collectively forming the core board. The JN5139 wireless microprocessor module, engineered by Jennic Company, is a specialized RF module tailored for expansion and testing, functioning within the 2.4 GHz frequency band [26]. This design allows users to efficiently implement wireless systems based on the IEEE802.15.4/ZigBee protocol, thereby optimizing both time and cost. The overall system plan encompasses remote monitoring centers, soil property information, meteorological information, the base station, and the ZigBee network, culminating in a robust architecture supporting the remote monitoring center's functionalities.

Within the crop growing area of the sprinkler irrigation system, the functionality is orchestrated through a network comprising sensor nodes, controller nodes, a coordinator node, and the base station computer. The core board serves as the foundation, equipped with diverse sensors to create sensor nodes, or alternatively, fitted with control boards to shape the controller nodes. In practical scenarios, controller nodes can also be endowed with sensors, effectively performing the dual role of both controller and sensor nodes. In situations where energy conservation for sensor nodes is imperative, and the base station is situated at a considerable distance, controller nodes can strategically operate as routers. In this capacity, they respond to the sensor nodes, facilitating communication through the nearest controller node. This approach ensures efficient information exchange, enabling the controller node to serve as an intermediary in conveying information from the sensor nodes to the base station computer.

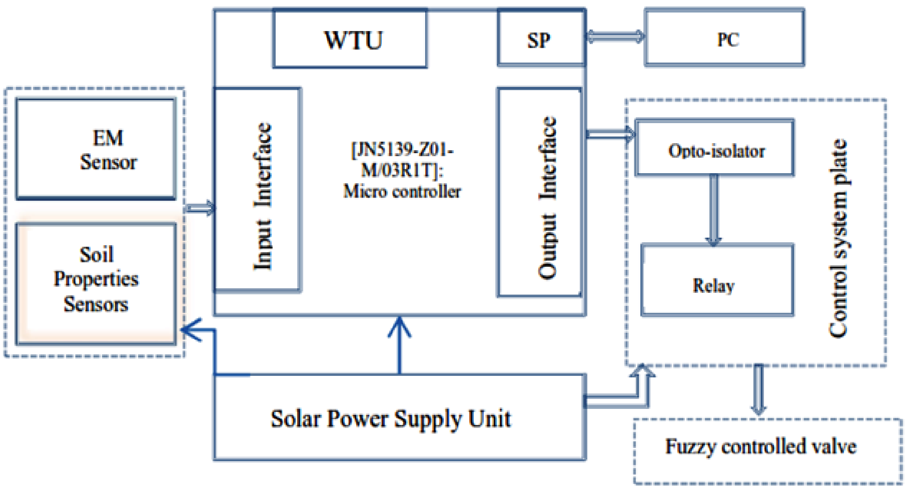

Figure 3. Structure of WSN with Zigbee Module.

The power supply module in this system is diversified into three categories: mains power, battery, and solar power. The selection among these categories depends on the specific node type and its corresponding requirements for transmit power and energy consumption. The coordinator node, which is connected to the base station and necessitates high transmitting power, is powered by mains electricity. This ensures a consistent and reliable power source for effective communication. The controller node, responsible for interfacing with the irrigation control panel to regulate electronically controlled valves for irrigation, typically draws power from commercial sources. Given that irrigation control panels and electronically controlled valves are commonly powered by commercial electricity, the controller node is suitably powered by mains electricity.

To prevent, electrical interference, the core board and irrigation control board employ couplers to achieve isolation. In contrast, the weather station-sensing controller node operates on solar power, harnessing energy from the sun for sustained functionality. Apart from these specifications, other nodes in the system are powered by batteries, providing a portable and flexible power solution for their respective roles. This diverse power supply strategy ensures an efficient and reliable operation tailored to the specific requirements of each node in the system.

3. Fuzzy Controller Design

The design of the fuzzy controller is in two parts. In the first part, the calculation of the evapotranspiration values, and the second part discussed the fuzzy-control strategies.

3.1. Obtaining Input Quantities

Crop water demand is multifaceted, influenced by various factors such as soil moisture indicators, environmental meteorological conditions (radiation, temperature, humidity, wind speed, etc.), specific crop types, and their distinct growth and development stages. Among the soil moisture indicators, soil moisture content is significantly change by changes in soil texture, and soil water potential from energy perspective, provides affective description of soil drought. Unlike moisture content, soil water potential is not directly influenced by soil texture, rendering it highly representative and universally applicable. Another critical factor in depicting crop water requirements is farmland evapotranspiration, which comprehensively integrates environmental meteorological conditions and crop types. This system selects soil water potential and farmland evapotranspiration as input quantities for the fuzzy control device. The EQ15 soil water potential sensor enables direct acquisition of soil water potential values, while farmland evapotranspiration is derive through a combination of calculation and measurement. Equation (1) represents the formula expressing farmland evapotranspiration under insufficient irrigation conditions [28].

$$\lambda E_a = \alpha \frac{s}{s+\gamma}(R_n - G) \tag{1}$$

where

E_a: is actual evapotranspiration

λ: is the latent heat of vaporization, α is a model coefficient (the value of α = 1.26 suggested by Priestley and Taylor for semi-arid regions),

s: is the slope of the saturation vapor density curve

γ: is the psychometric constant

R: is net radiation

G: is soil heat flux.

This strategic selection of input parameters ensures a comprehensive and accurate representation of crop water requirements in the system. The pivotal aspect in the determination of evapotranspiration lies in the calculation method, with numerous approaches available. Among them, the Priestley and Taylor method is most widely adopted. Research indicates that irrespective of whether it’s applied in arid or humid regions, the Priestley and Taylor method consistently demonstrates the highest level of calculation accuracy [27]. Based on energy balance and aerodynamic principles, this method boasts a comprehensive theoretical foundation, with exceptional precision in its calculations. Consequently, it is regarded as a standardized method, enjoying widespread adoption globally.

The Priestley and Taylor method's reliability and accuracy make it the method of choice for calculating evapotranspiration in various geographical and climatic contexts.

This approach necessitates meteorological data, including solar radiation, wind speed, air temperature, and humidity, among other factors. The World Food and Agriculture Organization (FAO) extensively details these requirements. In this system, the Priestley and Taylor formula relies on meteorological information, obtained through micro weather stations strategically positioned near the crop planting areas (refer to "1 System Overall Design" for specific details). These stations serve as vital components in gathering the essential meteorological data for accurate calculations within the Priestley and Taylor method.

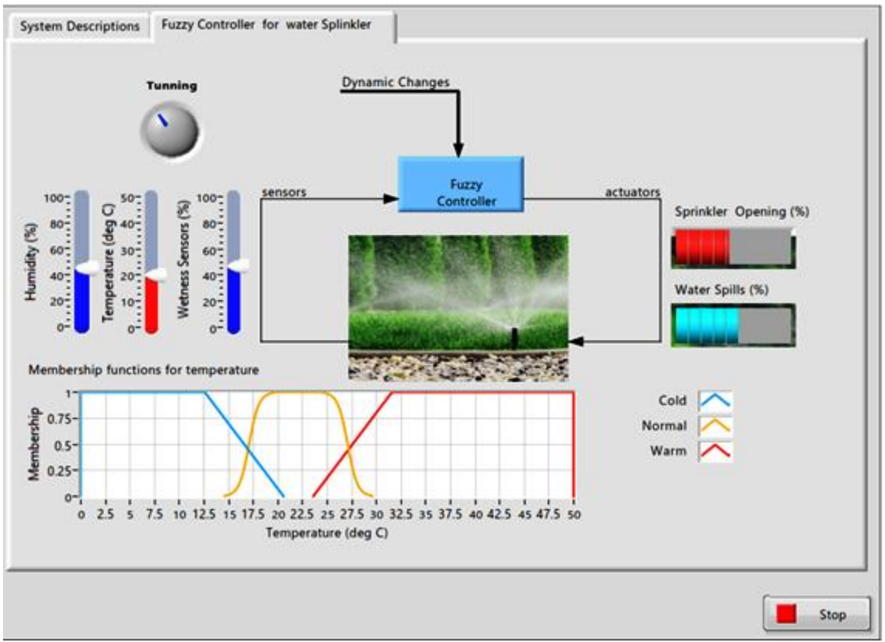

Figure 4. Simulation of real-time fuzzy controlled irrigation system (Lab View).

3.2. Fuzzy Control Strategy

Fuzzy logic is the best mathematical tool for modeling real-world control systems [29]. It is used in various fields, as reported in the literature [30–33]. As shown in Figure 4, the input of the fuzzy controller is the soil water potential value WP, Farmland evapotranspiration, the output is irrigation time WT. To ensure proper precision degree, three variables all define five language variables: very small (VL), small (L), medium (M), Large (H), and Very Very (VH). When choosing a membership function (MF)Considering that the triangular MF has a simple form and high calculation efficiency, it is particularly suitable in situations which require real-time implementation, so this system chooses triangle MF, e.g., Figure 5 shows the membership function of farmland evapotranspiration.

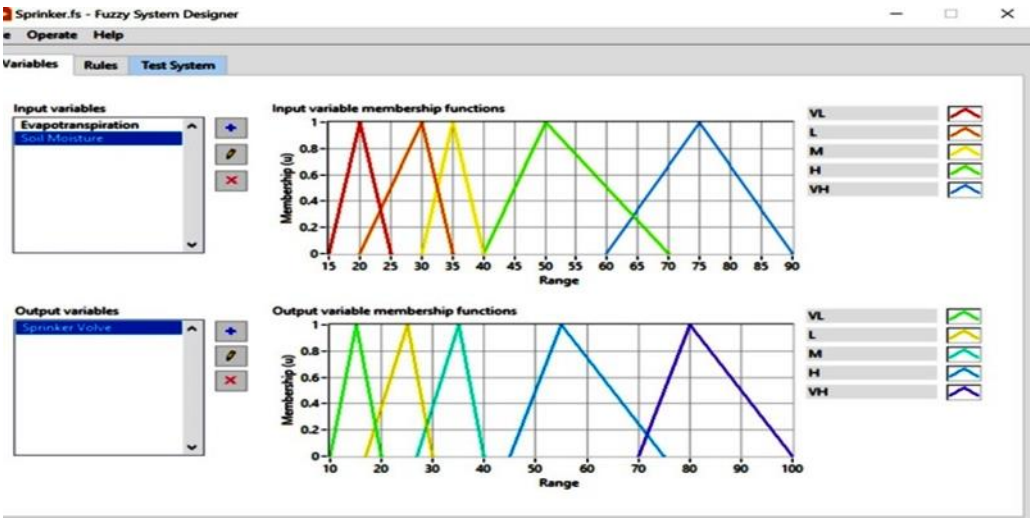

Figure 5. Membership functions.

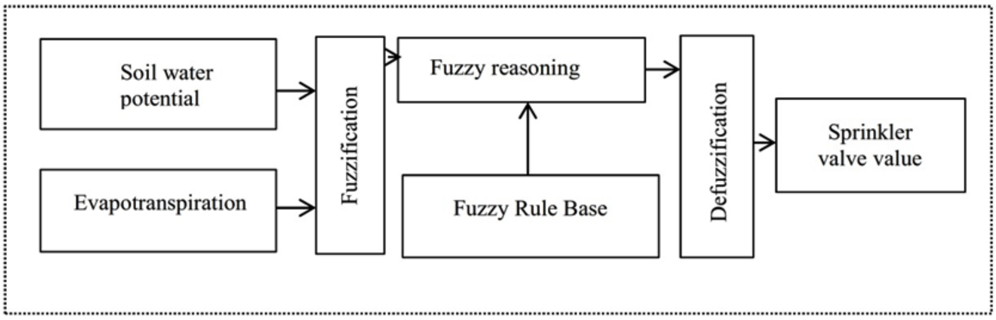

Figure 6. Structure of fuzzy controller.

(1) Fuzzification: Convert the precise value of the input variable into an appropriate domain of discourse fuzzy language variable value, that is, determine the variation range of each input and output quantity and its domain of discourse on fuzzy linguistic variables. For example, the farmland evapotranspiration cg/h The change range is [0, +1], and its domain of discussion is selected X= {0, 0.23, 0.46, 0.69,0.92}.
(2) Fuzzy inference: based on the knowledge base and through a certain inference engine System, the process of obtaining fuzzy output value from input value. Inference rule master Summarize based on experience and get the rules expressed in the "IF-THEN" statement. According to experience, when the soil water potential is lower than the lower limit, the soil is water scared. At this time, regardless of the level of farmland evapotranspiration, crops require a large amount of irrigation. It as a fuzzy inference rule, "if WP is VL, then WT is VH". The fuzzy inference rule base is in Table 1. In practical applications, it is also necessary to the rules are adjusted according to different situations and the optimal irrigation plan is gradually formed.
(3) De-fuzzy: multiply the results obtained by fuzzy inference by the scaling factor, Obtain the precise output value of the control quantity required by the system. This system adopts quality method is used to defuzzyfy and obtain the opening time of the sprinkler's irrigation head control valve. The fuzzy controller is design using the Lab VIEW software toolkit.

Table 1. Inference rules of Sprinkler control.

Evapotranspiration	Soil Water Potential (WP) Title 3				
	VL	**L**	**M**	**H**	**VH**
VL	VH	H	M	L	VL
L	VH	H	M	L	VL
M	VH	H	M	L	VL
H	VH	H	M	L	VL
VH	VH	VH	H	M	L

4. System Application and Verification

We test the system in drip irrigation in Mahoba district in Uttar Pradesh. The farmer uses a ground-fixed drip irrigation system, with one irrigation system for each plot. A butterfly shaped water transmission and distribution pipe network with multiple branch pipes, with electronically controlled valves installed on the main pipes. At the end, each electronically controlled valve is connected to a wireless sensor network controller node connected, and the controller node control the drip irrigation time of the plot. For experimental purpose three plots are selected, and the distance between the controller nodes of each plot is 60 to 100 m, while sensor nodes are evenly distributed in approximately square areas of each plot (each plot contains 1 to 2 sensor nodes), and the base station (coordinator node) is the farthest node 300 m. Experiments show that when the node distance is 250 m, a single The communication bit error rate is less than 2.2%, system adopts multiple repeated communication methods. Comprehensive judgment further improves communication reliability.

In addition, the system power control valve is well controlled and operating condition is excellent. Table 2 displays the observed values of the opening sprinkler valve in percentage based on four parameters. We took one to ten readings in the month of March 2023 in the frequently changed temperature values of the semi-arid regions when other parameters were approximately same. Reading samples 11–20 were taken in the month of May 2023, when the temperature values in this region are continuously rising and other parameters are fluctuating. We took third phase of readings (21–30) in July 2023, when the humidity was rising while temperature values were not changing frequently. We took last phase reading in the month of September 2023, which is the time of rain. Humidity reaches its highest value this month, and the other parameters change frequently. The sprinkler valve opening values are clear and indicate that there is limited use of water for irrigation. The outcome of this system claims to save 10% water compared to the traditional irrigation system.

Table 2. Simulation Observed Values.

#	Temp	Humidity	Atom-presser	Wind speed	Valve Open in %
1	37.26	9	985	4.62	60
2	31.87	13	987	1.23	50
3	29.95	15	988	2.05	45
4	27.91	19	987	1.68	40
5	26.28	22	988	0.65	46
6	32.7	16	990	0.17	47
7	39.18	10	990	1.22	46
8	40.28	8	986	4.87	73
9	39.06	9	984	3.73	70
10	33.5	13	986	1.12	72
11	43.27	14	986	1.68	65
12	42.43	16	984	3.48	52

13	43.34	17	985	2.67	54
14	43.23	12	987	2.34	67
15	44.65	8	987	3.51	69
16	41.65	7	983	5.11	73
17	43.13	7	982	4.14	75
18	42.03	11	983	2.38	62
19	41.71	14	984	2.47	58
20	43.95	18	983	2.72	63
21	34.99	21	983	2.09	56
22	35.12	14	986	2.29	51
23	35.59	9	985	5.44	48
24	34.96	7	982	5.26	57
25	36.29	8	980	4.06	68
26	35.41	11	982	2.3	62
27	33.51	13	983	2.99	61
28	31.46	14	982	2.42	53
29	32.08	16	983	1.87	58
30	35.83	56	985	2.25	45
31	32.07	68	985	4.53	43
32	33.37	58	982	4.72	30
33	31.69	70	980	4.55	45
34	35.66	78	983	1.69	35
35	33.37	93	984	2.4	24
36	31.74	96	983	0.91	20
37	31.54	98	984	1.42	17
38	33.99	94	986	1.47	19
39	34.41	97	985	3.19	18
40	33.56	93	982	4.66	20

5. Conclusions and Discussion

1. We propose to combine ZigBee wireless sensor network with fuzzy control. We designed a method suitable for precision irrigation, a corresponding system is adopted. By collecting and analyzing the soil water potential and farmland evapotranspiration in crop planting areas, the accurately obtain crop water requirements and realize automatic, positioning, real-time and appropriate irrigation. The system is economical and practical, especially suitable for small and medium-sized irrigation areas. Pass-tested in drip irrigation in Panwari Block, Mahoba District, Uttar Pradesh. Preliminary trials on the farm have shown that the system has reliable communication high control accuracy in good running condition.
2. Propose the corresponding wireless sensor network node-design method and verify it proves the feasibility of ZigBee wireless sensor network for remote irrigation control.
3. Designed an information collection method for accurately determining crop water requirements. Case, and established a model based on the Priestley and Taylor formula and fuzzy numbers multi-sensor data fusion method learned, which comprehensively considers soil water potential Ambient temperature, humidity, solar radiation and wind speed related to farmland evapotranspiration The influence of other factors improves the accuracy of decision-making.
4. The wireless sensor network designed in this article adopts star network topology structure, requiring each node to receive data so that the node transmit power is

consistent with the energy consumption is high, and new network topology and networking we will further study in the future.

This strategy aims to lower node energy consumption for large-area and high-capacity irrigation systems.

Author Contributions: Conceptualization, R.P. and A.K.S.; Methodology, R.T. and A.K.S.; Software, R.P.; Validation, R.P. and R.T.; Formal Analysis, A.K.S.; Investigation, R.T.; Resources, R.P.; Data Curation, R.P. and R.T.; Writing Original Draft Preparation, R.P. and R.T.; Writing Review & Editing; R.T.; Visualization, A.K.S.; Supervision, R.P. and R.T.; Project Administration, R.P., R.T. and A.K.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

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