Development of an Integrated Feedback and Feed-Forward Algorithm for Smart Irrigation Based on Fuzzy Logic

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Abstract

Agriculture is the world's biggest water consumer, hence the consideration of creating water saving measures. This has led to increase in research on smart irrigation systems over the years. In traditional irrigation the crop is irrigated every day with a certain amount of water base on farmer's experience without putting the plant's water need into consideration, this leads to water wastage. Smart irrigation is the solution to this, smart irrigation uses sensors, actuators and internet of things (IoT) to efficiently irrigate in the right place, at the right time and in the right amount. In this work an integrated feedback and feedforward algorithm for smart irrigation based on fuzzy logic was developed. The algorithm employs sensors for feedback and a typical water balance method based on crop evapotranspiration (ETc) which ensures that the soil and plant water inputs must balance the expected output (evapotranspiration) for feedforward. The algorithm employs fuzzy logic controller to efficiently control the percentage of valve opening according to the effect of four input parameters; soil water content (SWC), ETc, air temperature and humidity, which are vital for crop growth making the algorithm efficient in practical scenario. The algorithm was simulated and evaluated using MATLAB and the results compared with existing related work, the result showed that the algorithm is cost effective as it greatly reduces manual labor, the algorithm saves water by 45% and has a higher crop yield as compared to traditional irrigation method.

Key words: Evapotranspiration, Fuzzy logic, Smart Irrigation, Algorithm, MATLAB

1.0 Introduction

Agriculture is one of the most important parts of survival for people around the world, In Nigeria, agriculture is one of the main sources of livelihood. Water plays a crucial role in plants life cycle, including germination, photosynthesis and nutrition processes. Most often, the water provided by natural precipitation is not enough to provide the amount of water needed by plants for a healthy growth (Sales et al., 2015). Water scarcity is one of the major concerns of today's agriculture, therefore efficient irrigation of agricultural land is important and can be accomplished with help of smart irrigation systems (Kokkonis et al., 2017).

In agriculture, improving crop yield is crucial to meet up growing demand of food for population increase. In order to advance crop productivity, there is an urgent need to shift from manual methods to automation (Krishnan et al., 2020).

Smart irrigation is a process of scheduling water supply efficiently to an agricultural field with the aid of actuators, sensors and IoT with no or less human intervention. The decision for watering is based on data collected through wireless sensor networks (WSN) from sensors and actuators, the primary goal of a smart irrigation system is to reduce water waste and provide correct balance for optimal plant life (Hasan et al., 2019).

Most of the existing methods for irrigation control can be classified into two namely (Casadesús et al., 2012) :

i. Feed-Forward Control: In feed-forward control the crop water need is estimated by water balance, where the soil and plant water inputs must balance the expected outputs (Casadesús et al., 2012).

ii) Feed-Back Control: Feed-back control is aimed at keeping the soil moisture of the soil or the plants' water stress within range. Example of irrigation control based on feedback is the use of sensors.

It typically consists of managing irrigation in order to keep the crop water status within controlled range.
Agriculture remains the World's biggest water consumer, with farming and food production accounting for up to 70% (World Bank, 2018), In Nigeria agriculture is one of the main source of livelihood, especially for people living in the rural areas which constitutes 65% of the populace (Bashir & Kyung-Sook, 2018). Also, with the exponential population growth, there is need to meet up with food demand for the population. One of the major contributors to water wastage in agriculture is traditional irrigation and low irrigation efficiency, currently according to FAO, 60% of water diverted or pumped for irrigation is wasted via runoff into waterways or evapotranspiration through plant surface and soil (Alomar & Alazzam, 2019).

Fuzzy logic is a form of soft computing method which accommodates the imprecision of the real world, unlike traditional hard computing soft computing exploits the tolerance for imprecision, uncertainty and partial truth to achieve tractability, robustness and low solution cost (Wang, 2015). Fuzzy logic provides a convenient way to map an input space to an output space using a list of If-Then statements called rules and membership functions. According to Hasan *et al.*, 2019 Fuzzy logic is basically representation of logic with many values, these values can be any real number between 0 and 1.

Unlike traditional logic, such as binary logic where variables may only take on two values True and False represented by 1 and 0 respectively, the variables in fuzzy logic may have a truth value that ranges in degree between 0 and 1. Instead of describing absolute Yes or No, the truth value or membership in fuzzy logic explains a matter of degree, 0 shows completely False, while 1 shows completely True, and any value within the range indicates the degree of True (Wang, 2015).

Some advantages of fuzzy logic include: fuzzy logic is easy to understand, Fuzzy logic is tolerant of imprecise data, fuzzy logic is flexible, it can model non-linear functions of arbitrary complexity, Fuzzy logic can be built on the experience of experts, fuzzy logic can be blended with conventional control techniques and it is based on natural language.

2.0 Literature Review

This section covers fuzzy set and fuzzy inference process and some related works on smart irrigation based on fuzzy logic.

2.1 Fuzzy Set and Fuzzy Inference Process

Fuzzy logic starts with the concept of a fuzzy set. A fuzzy set is a set without a clearly defined boundary, it contains elements with a partial degree of membership (Wang, 2015). In classical well-defined set, the membership of elements complies with binary logic, either the element belongs to the set or it does not belong to the set but in fuzzy set theory, it contains elements with degree of membership between completely belonging to or completely not belonging to the set. This is because a fuzzy set does not have a clearly defined boundary, its boundary is described by membership functions with degree of membership of elements ranging from 0 to 1.

An example of a fuzzy set is shown in figure 2.1 which describes the criterion for pass mark for students, a student with a score equal or greater than 70% is defined as an element in this set with full degree of membership, in this case a student with a score of 80% definitely has a full degree of membership (with value of membership = 1), another student with a score of 15% is far away from the pass mark (70%), so it has zero degree of membership (with value of membership = 0), in other words completely does not belong to the set, another student with a score of 60% fairly close to the pass mark and can be said to have partial degree of membership and a value of membership (0.8) is decided by the feature of membership function.

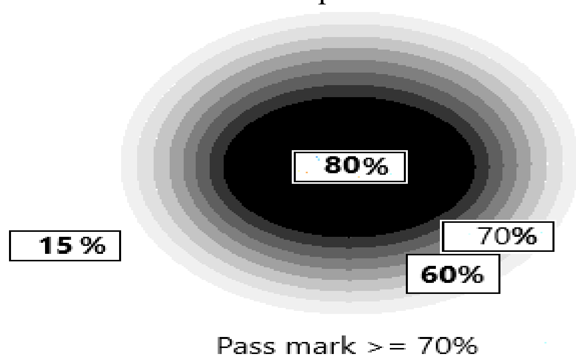


Figure I: Fuzzy Set 'Pass Mark'

Source: Wang (2015)

Fuzzy inference is the process of mapping a given input variable to an output space using fuzzy logic based deducing mechanism which is comprised of If-Then rules, membership functions and fuzzy logical operations, Fuzzy inference systems have been successfully applied in fields such as automatic control, data classification, decision analysis, expert systems and computer vision (Wang, 2015). The Mamdani type fuzzy inference process which was used in this work consists of five (5) steps as follows:

i. Fuzzify input variables
ii. Apply fuzzy operator
iii. Apply implication method
iv. Apply aggregation method
v. Defuzzification

2.2 Related Works on Smart Irrigation Based on Fuzzy Logic

In Alomar & Alazzam (2019), they proposed a system that consists of sensors and they employed fuzzy logic for irrigation control, they employed a Mamdani fuzzy logic controller to control water flow from a water pump, the used two inputs; soil moisture and air temperature and one output, water flow. Soil moisture and air temperature are continuously monitored using sensors and the water flow is adjusted accordingly, they basically used fuzzy logic to maintain the soil moisture at a preset value. Their work only considers feedback approach and doesn't employ feedforward approach, also their system utilizes only two input parameters which makes it difficult to capture some environmental factors that are necessary to predict irrigation need.

Krishnan *et al*. (2020) proposed a fuzzy based smart irrigation system that incorporates sensors, GSM technology and solar power, sensors to sense environmental factors, GSM technology to send SMS to farmers regarding conditions of the soil and motor status and the solar power to save energy. Data from sensors in the field are used to control a motor ON and OFF status using fuzzy logic controller. The algorithm works by initializing GSM modem as soon as power supply is turned ON, the processor checks the availability of solar energy with the help of a light dependent resistor (LDR), if solar energy is available the system is run using the solar power, the processor checks the soil water content whose threshold is set to a predefined value, once the soil moisture content is greater than the set threshold the motor is tuned ON, This system considers power saving by employing solar power to run the pump.

In Jaiswal & Ballal (2020), they employed fuzzy logic and IoT to perform irrigation using soil moisture, humidity, air temperature and reservoir water level as input parameters to control the percentage opening of a valve. Their work considered energy consumption by ensuring valve is open only at lower supply tariff, if tariff is high irrigation is rescheduled.

In the aforementioned research works, it can be seen that several authors Alomar & Alazzam, (2019); Kokkonis *et al*. (2017); Krishnan *et al*. (2020); Hasan *et al*. (2019); Munir *et al*. (2018) proposed smart irrigation systems that employed sensors and fuzzy logic for irrigation control, these works use only feedback mechanism from sensors to control irrigation. Their work can be improved by adopting a combination of feedforward and feedback mechanism.

Munir *et al*. (2018) proposed a fuzzy based smart irrigation system for a tunnel farm that uses internet of things (IoT) and sensors to capture field and plant parameters and their need for watering, the system includes a mobile phone application interface that is used to continuously monitor and control the system. The system uses fuzzy logic to decide the watering quantity of the field considering soil moisture level, humidity and temperature.

3.0 Methodology

The software used for simulation and evaluation is the MATLAB simulation tool from MathWorks, MATLAB is equipped with a toolbox for fuzzy logic implementation and MATLAB supports interoperability with other programming languages.

The Fuzzy Inference System (FIS) was built using the tool box available in MATLAB. The fuzzy logic implementation focuses on the decision-making of the Algorithm, the fuzzy system has four inputs: ETc, Soil moisture, Air Temperature and Humidity and one output: Valve control. The fuzzy inference system is shown in the figure I.

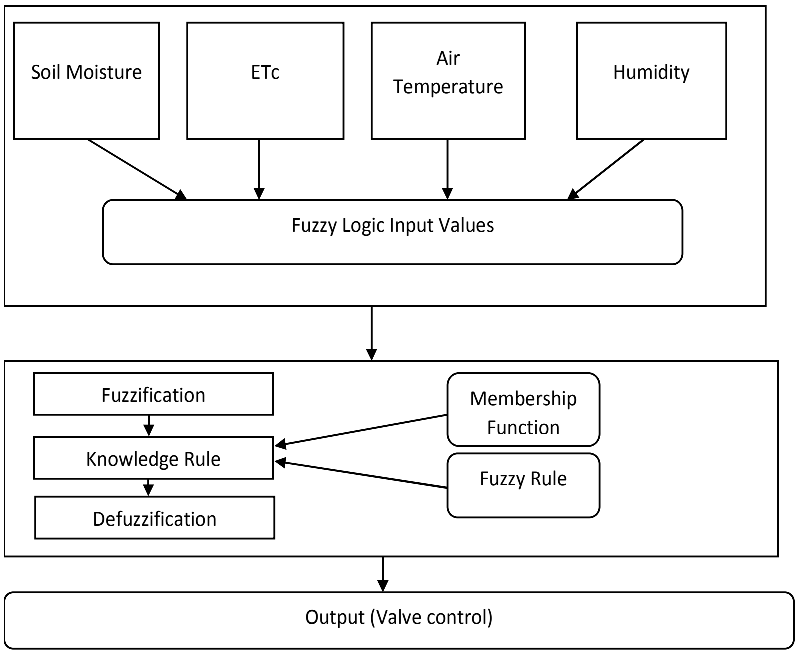


Figure II: Fuzzy Inference System (FIS)
Source: Lawrence et al (2023)

Each input parameter consists of three membership functions, the membership functions values and fuzzy rules are framed using the weighted methodology. The membership function for each parameter is given in Table I.

Table I: Inputs and Membership Functions

INPUTS	MEMBERSHIP FUNCTIONS		
ETc	Low	Medium	High
Soil Moisture	Dry	Medium	Wet
Air Temperature	Cold	Warm	Hot
Humidity	Dry	Medium	Wet

The number of fuzzy rules is given as Nm where N is the number of membership functions and m is the number of inputs. Since the FIS has four inputs with three membership functions each, 81 fuzzy rules were generated for the FIS.

To evaluate the performance of the algorithm, the algorithm was simulated and evaluated using MATLAB and results were compared with the work of Jaiswal & Ballal (2020).
The metrics used to evaluate the performance of the algorithm are:

i. Soil Moisture: The soil moisture gives the indication of water in the soil; it is the most vital factor for deciding whether to irrigate or not. Soil moisture gives the water stress in the soil and it is needed to know the amount of water to be dispensed to the crop (Touati et al., 2013).

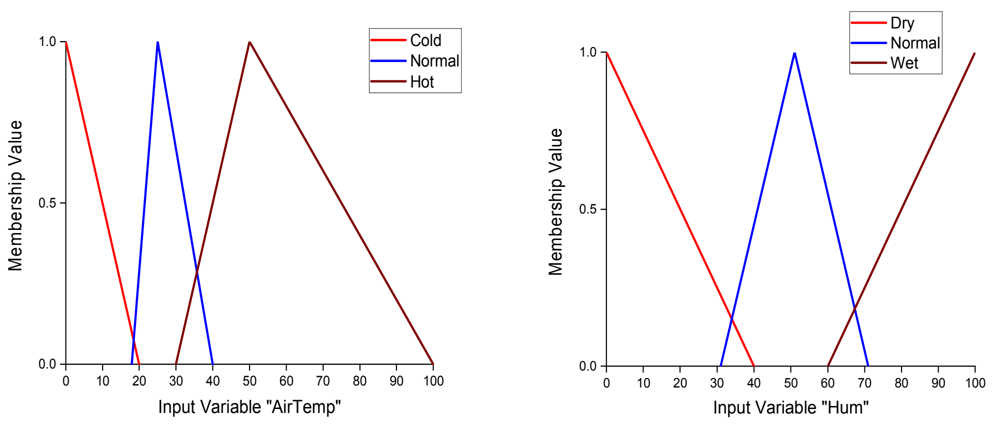
ii. Air Temperature: The air temperature gives the measure of the environmental temperature, it is important because many plants are sensitive to air temperature during irrigation especially in extreme weather conditions, at very hot weather condition irrigation should be avoided (Kokkonis et al., 2017).

iii. Humidity : This indicates the humidity of the environment, a high (wet) humidity is responsible for rise in the rate of precipitation which replenishes the ground water level and also reduces the crop irrigation need (Jaiswal & Ballal, 2020). Therefore, it is important to observe the humidity in order to make decisions on irrigation requirement.

iv. Crop Evapotranspiration : This is the evaporation from the soil surface and the transpiration through plant surface (Davis et al., 2009), it is an estimate of the loss of water from both the plant and the soil. This metric is important to estimate the amount of water lost so it can be complemented through irrigation.

4.0 Results and Discussions

The work Implements a fuzzy inference system (FIS) that evaluates four input variables for deciding the percentage of valve opening based on fuzzy logic. This section shows the result of the fuzzy logic implementation. As shown in figure III the triangular membership functions was used for the input variables and the trapezoidal membership function was used for the output variable. All membership functions were assumed to have a universe of discourse of 0-100. For the purpose of this work the bigger number represents a high value and the smaller number represents a low value. The rules were implemented using the weighted methodology of Wang,2015 where weights are introduced into the input variables. 81 fuzzy rules were developed for the system.



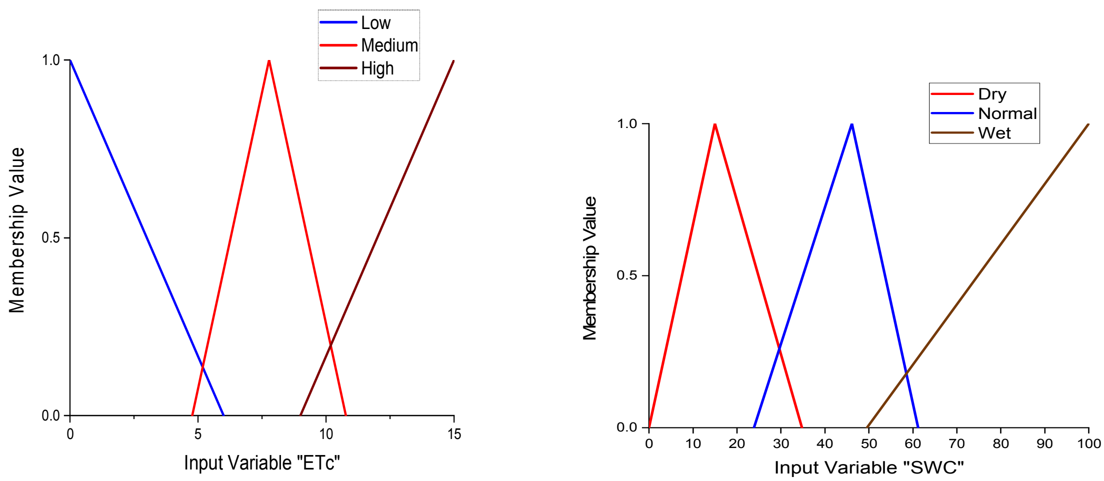


Figure III: Membership Function for The Inputs

Source: Lawrence et al (2023)

As can be seen in figure IV this work utilizes the Min-Max inference rule base with AND connectives between the inputs. These fuzzy rules are aggregated on the inputs to determine the percentage of valve opening for every possible scenario of input.

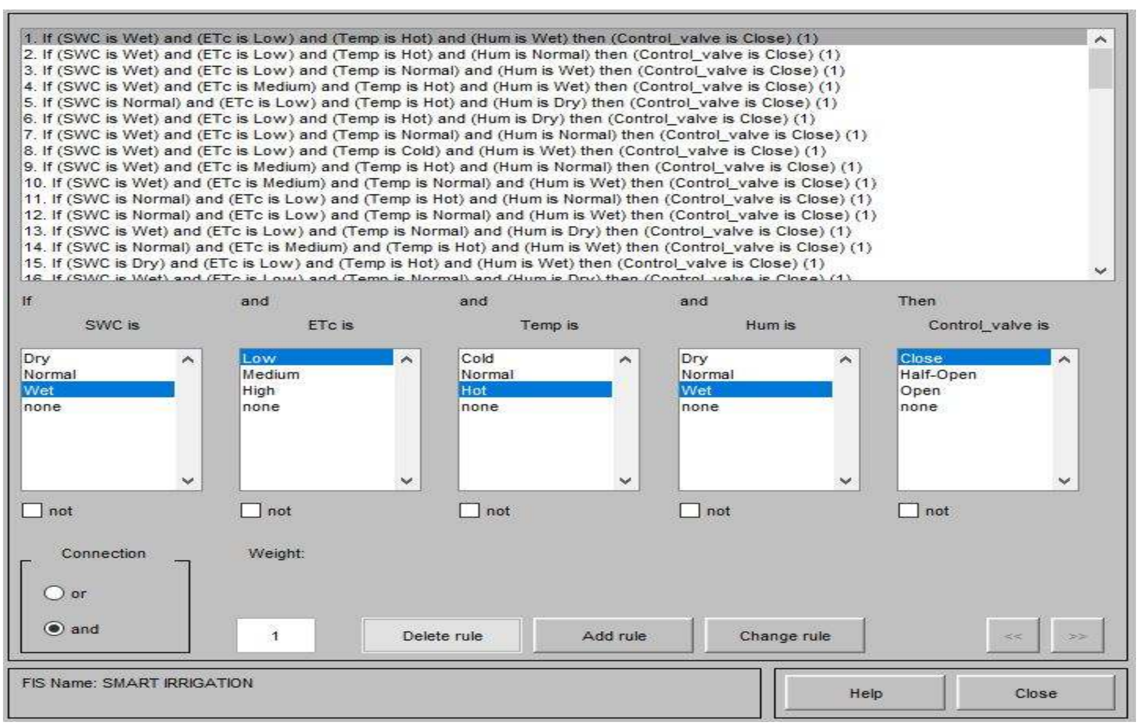
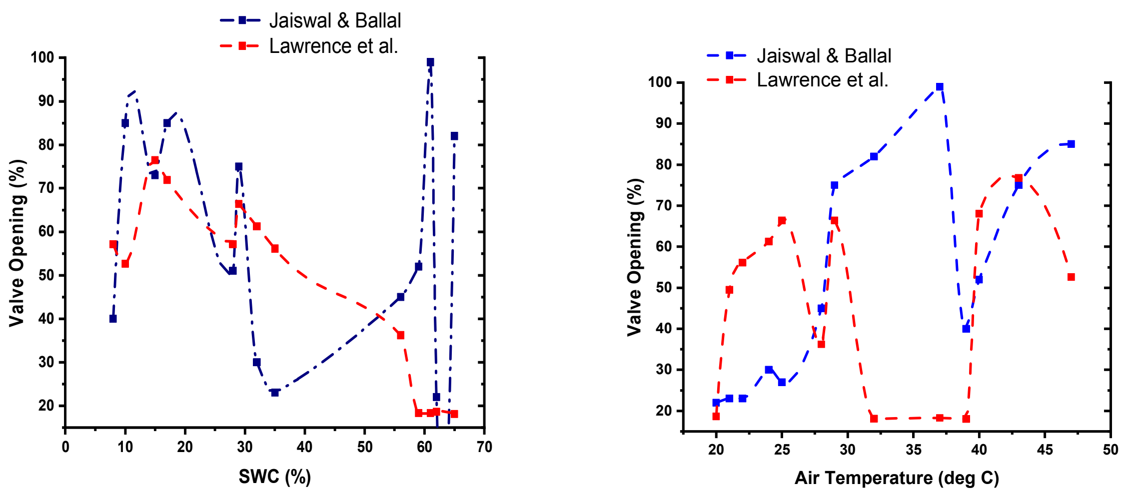


Figure IV: Rules settings for The FIS system

Source: Lawrence et al (2023)



(a) (b)

Figure V: Result Comparison of "SWC" and "Air Temp"

Source: Lawrence et al (2023)

Figure V (a) shows that when SWC is 8%, valve opening is 40% in the work of Jaiswal & Ballal and valve opening is 57.1% in this work. Figure V (b) shows that when air temperature is 390C, valve opening is 40% in the work of Jaiswal & Ballal and 18% in our work. Notice that in this work when temperature is high valve opening is low, this is because it is preferable to schedule irrigation at low temperatures when the weather condition is favorable.

5.0 Conclusion and Recommendations

In this work an integrated feedback and feed-forward smart irrigation algorithm based on fuzzy logic was developed. The developed algorithm uses sensor data for feedback and crop evapotranspiration (ETc) for feedforward. The fuzzy controller efficiently controls the percentage of valve opening based on soil water content (SWC), crop evapotranspiration (ETc), air temperature and humidity.

The evaluation and comparison of the algorithm shows that it is cost effective as it reduces manual labor to a great extent, the algorithm saves 45% water which is better as compared to other existing related research, the algorithm has a higher crop yield as compared to traditional irrigation method.

More work can be done to further improve the algorithm by incorporating artificial intelligence and machine learning to enable the algorithm perform irrigation needs prediction and irrigation dose (volume) prediction, this way even if the sensors fail the system will be able to predict future irrigation needs and their dosage. Energy consumption can also be considered in future works, where energy supply tariff can be included as an input parameter and irrigation is scheduled only at low tariffs and rescheduled at high tariff.

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