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Implementation of Fuzzy Logic to Control Soil Moisture Level in Arduino-Based Rice Fields

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Abstract

In Indonesia, where the agricultural sector is pivotal in the economy and most of the population are farmers, effective soil moisture control is crucial for optimizing crop production. This study investigates the application of modern technology, particularly Arduino microcontrollers utilizing Fuzzy Logic, to enhance irrigation management in rice fields. Given the challenges of irregular water supply due to geographical and temporal variations, additional infrastructure such as waterways, dams, and pumps are indispensable for regulating water distribution. By integrating Arduino microcontroller technology with Fuzzy Logic, precise and adaptive soil moisture management can be achieved, ensuring optimal water usage and improving crop yields. This research contributes to advancing sustainable agriculture in Indonesia, addressing the pressing need for food security amidst a growing population.

Keywords: Agriculture, Arduino Microcontroller, Fuzzy Logic, Soil Moisture.

INTRODUCTION

Most of Indonesia's population act as farmers in an economy dominated by the agricultural sector (Iksan *et al.*, 2022). A critical aspect of efforts to increase agricultural productivity is the control of soil moisture levels, which is crucial in optimizing plant growth and resource use efficiency. Rice field soil is used to grow various edible crops continuously throughout the year or alternately. “Paddy soil” is not a scientific classification but a general term similar to forest soil, plantation soil, and other agricultural soils.

In the evolution of agricultural technology, developing soil moisture control systems is an appropriate response to the challenges of maximizing agricultural yields. As water supply is often insufficient due to location and time factors, additional infrastructure such as waterways, dams, water pumps, gutters, and the like are required. Such infrastructure aims to deliver water from its source to the intended location while regulating the amount delivered according to the need (Setiadi *et al.*, 2018).

Therefore, using Arduino microcontroller technology with a Fuzzy Logic approach is essential to optimize irrigation arrangements in rice fields. By utilizing this technology, farmers can effectively manage soil moisture levels by considering various factors that affect them accurately and adaptively. This approach allows the irrigation system to provide additional water to the crops only when needed, thereby increasing the efficiency of water resource use and overall crop yields.

Thus, developing and applying technologies such as the Arduino microcontroller with a Fuzzy Logic approach reflect advancements in the agricultural sector and provide an effective solution in facing the challenges of complexity in controlling soil moisture levels. This also aligns with global efforts to sustainably increase farm productivity and ensure adequate food availability for the growing population.

Fuzzy is linguistically defined as fuzzy or vague. In fuzzy logic, a value can be large or small simultaneously. The concept of degree of membership is introduced, which ranges from 0 (zero) to 1 (one), in contrast to a strict set that only has a value of 1 or 0 (yes or no). Fuzzy logic is a decision-making method that makes it easy to find a solution to a problem with limited variables (Dwirohmatun Sugianti *et al.*, 2019). In fuzzy logic theory, a value can simultaneously have a degree of truth and error. However, the amount of existence and error depends on its membership weight. Thus, fuzzy logic is suitable for managing soil moisture levels influenced by various variables.

The journal (Nasron *et al.*, 2019) proposed an automatic watering system that can adjust to plants' water needs based on soil conditions, temperature, light, and humidity. Using a Wi-Fi-connected Esp-8266 microcontroller, this system aims to assist farmers in caring for plants efficiently and effectively by providing precise control of plant watering based on changing environmental conditions.

In this context, this research explores the potential of applying Fuzzy Logic technology to optimize irrigation settings in rice fields. Using an Arduino microcontroller connected to sensors that measure humidity and temperature, the system will be able to control the watering of rice fields automatically. Thus, this system will help farmers manage water resources more efficiently, increase agricultural productivity, and ultimately, positively contribute to food security.

METHODS

The type of research used is qualitative, using interview techniques. The interview technique collects subjective data such as opinions, attitudes, and behaviours of sources related to a phenomenon under study (Hansen, 2020).

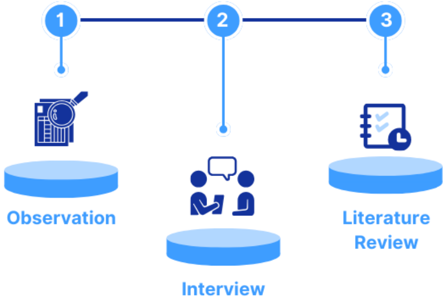

Figure 1. Deployment Method Flow

- Observation
  Researchers conducted direct monitoring on Jl. Nagrog RT. 2 RW. 4, Ciampea District, Bogor Regency, West Java, to observe the temperature and humidity conditions in the rice field area.
- Interview
  Researchers conducted face-to-face interactions with rice field owners to obtain relevant information.
- Literature Review
  Researchers acquire data through library references or search for information from various sources (Pusparani, 2021).

In this study, researchers adopted the Fuzzy Logic Mamdani method to regulate the humidity level in rice fields. This approach was chosen for its flexibility, ability to handle uncertain data, and intuitive nature that can be accepted by various stakeholders (Fauzi & Ardhiansyah, 2022). The method involves a series of stages as follows:

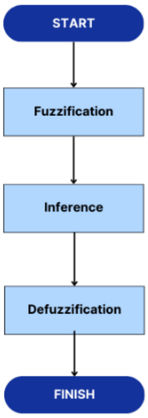

Figure 2. Stages of Fuzzy Logic

- Fuzzification
  This stage involves converting quantitative data such as temperature and humidity into fuzzy sets with membership values at specific intervals. This process, called fuzzification, is very useful in modelling uncertain or incomplete data, thus improving decision-making capabilities (Siregar *et al.*, 2023).
- Inference
  The inference stage is to explain the relationship between input and output variables, where the variables will be processed and will produce a decision. The relationship between input and output is usually used as if-then (Siregar *et al.*, 2023).
- Defuzzification
  Defuzzification is a stage in fuzzy data processing that converts fuzzy values represented as output fuzzy sets with their membership functions into concrete or firm (crisp) values. This process is essential to return fuzzy data into a form that is easier to understand and use in decision-making or further analysis (Siregar *et al.*, 2023).

RESULTS AND DISCUSSION

Arduino microcontroller technology with a Fuzzy Logic approach in regulating irrigation of paddy fields has excellent potential to improve water resource use efficiency and overall agricultural productivity. By accurately and adaptively considering factors affecting soil moisture levels, this system can provide additional water to paddy fields only when needed, reducing water wastage and increasing crop yields.

Circuit Schematic

The circuit schematic in **Figure 3** includes various essential components that play a role in automatically controlling the irrigation system. The Arduino Uno is the control centre, taking data from the DHT22 temperature, humidity, and soil moisture sensor. The data from these two sensors determines when the fields require sufficient moisture according to optimal environmental conditions. In addition, the motor driver is used to control the servo motor in charge of opening and closing the irrigation door so that the amount of water supplied can be efficiently regulated based on the needs of the plants.

Using temperature and humidity sensors ensures that the plants get water according to the environmental conditions in which they grow, reducing the risk of underwatering or overwatering, which can be detrimental to the plants. Integrating the Arduino Uno, sensors, and motor drivers is critical to creating an automated and efficient irrigation system, helping farmers better manage crop watering and increase crop yields. This circuit scheme is essential for developing innovative and sustainable irrigation systems.

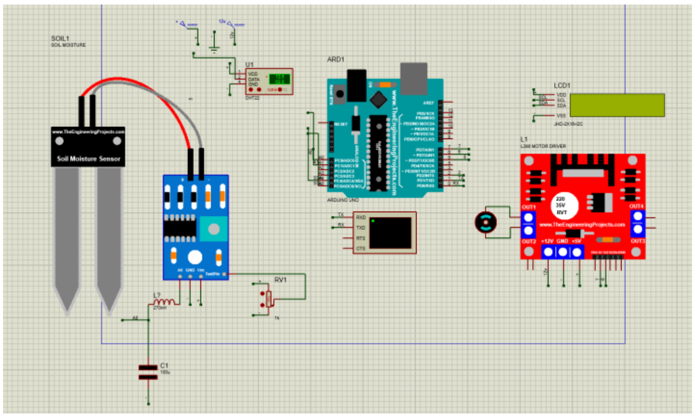

Figure 3. Circuit Schematic

Fuzzification

Fuzzification is one of the stages in data processing using fuzzy logic. This stage converts firm input data into fuzzy values that describe vagueness or uncertainty. With fuzzy logic, input data often cannot be expressed definitively as “true” or “false” but has a degree of membership in a fuzzy set that reflects how close the data is to the desired condition. The fuzzification process involves converting the input data into a fuzzy set with an appropriate membership function.

Table 1 displays the input data for humidity and temperature. This data is used in the research to determine the moisture and temperature state categories to be used in the irrigation control process.

Table 1. Soil Moisture and Temperature Input

Input			
State	**Soil Moisture (%)**	**State**	**Temperature (°C)**
Dry	[0-40]	Cold	[0-20]
Moist	[40-60]	Medium	[20-30]
Wet	[60-100]	Hot	[30-35]

Table 2 shows the results of measuring humidity and temperature conditions to determine the amount of water to be applied to the field. This helps adjust watering according to the needs of the plants based on the measured environment.

Table 2. Watering Ouput

Output	
State	**Watering (ml)**
Low	[0-300]
Medium	[300-700]
High	[600-1000]

Building Fuzzy Membership Sets

This stage is the determination of the membership set based on existing data. This step is essential because the membership set will be used to determine the degree of membership.

Soil Moisture Input membership set

The membership function for the soil moisture input variable is divided into three fuzzy sets. Each uses a trapezoidal curve. The membership function for the soil moisture input variable in this study is divided into three fuzzy sets: Dry, Moist, and Wet.

$$
Fx(Soil\ Moisture)\begin{cases} Dry = \begin{cases} x < 0 \rightarrow 0 \\ 0 = x = 20 \rightarrow 1 \\ 20 < x \leq 40 \rightarrow \dfrac{d-x}{d-c} \\ x > 40 \rightarrow 0 \end{cases} \\ Moist = \begin{cases} x < 40 \rightarrow 0 \\ 40 < x \leq 45 \rightarrow \dfrac{x-a}{b-a} \\ 45 = x = 55 \rightarrow 1 \\ 55 < x \leq 60 \rightarrow \dfrac{d-x}{d-c} \\ x > 60 \rightarrow 0 \end{cases} \\ Wet = \begin{cases} x < 60 \rightarrow 0 \\ 60 < x \leq 80 \rightarrow \dfrac{x-a}{b-a} \\ 80 = x = 100 \rightarrow 1 \\ x > 100 \rightarrow 0 \end{cases} \end{cases}
$$

Temperature Input membership set

The membership function for the temperature input variable is divided into three fuzzy sets. Each uses a trapezoidal curve. The membership function for the temperature input variable in this study is divided into three fuzzy sets: Cold, Medium, and Hot.

$$
Fx(Temperature)\begin{cases} Cold = \begin{cases} x < 0 \rightarrow 0 \\ 0 = x = 10 \rightarrow 1 \\ 10 < x \leq 20 \rightarrow \dfrac{d-x}{d-c} \\ x > 20 \rightarrow 0 \end{cases} \\ Medium = \begin{cases} x < 20 \rightarrow 0 \\ 20 < x \leq 24 \rightarrow \dfrac{x-a}{b-a} \\ 24 = x = 26 \rightarrow 1 \\ 26 < x \leq 30 \rightarrow \dfrac{d-x}{d-c} \\ x > 30 \rightarrow 0 \end{cases} \\ Hot = \begin{cases} x < 30 \rightarrow 0 \\ 30 < x \leq 33 \rightarrow \dfrac{x-a}{b-a} \\ 33 = x = 35 \rightarrow 1 \\ x > 35 \rightarrow 0 \end{cases} \end{cases}
$$

Membership set of Watering Output

The membership function for the watering output variable is divided into three fuzzy sets. Each uses a triangular curve. The membership function for the watering output variable in this study is divided into three fuzzy sets: Low, Medium, and High.

$$Fx(Watering)\begin{cases} Low = \begin{cases} x < 0 \rightarrow 0 \\ 0 < x \leq 150 \rightarrow \dfrac{x-a}{b-a} \\ x = 150 \rightarrow 1 \\ 150 < x \leq 300 \rightarrow \dfrac{c-x}{c-b} \\ x > 300 \rightarrow 0 \end{cases} \\ Medium = \begin{cases} x < 300 \rightarrow 0 \\ 300 < x \leq 500 \rightarrow \dfrac{x-a}{b-a} \\ x = 500 \rightarrow 1 \\ 500 < x \leq 700 \rightarrow \dfrac{c-x}{c-b} \\ x > 700 \rightarrow 0 \end{cases} \\ High = \begin{cases} x < 600 \rightarrow 0 \\ 600 < x \leq 800 \rightarrow \dfrac{x-a}{b-a} \\ x = 800 \rightarrow 1 \\ 800 < x \leq 1000 \rightarrow \dfrac{c-x}{c-b} \\ x > 1000 \rightarrow 0 \end{cases} \end{cases}$$

Fuzzy Rules

Figure 4 illustrates the process of creating fuzzy rules. In this process, the user only needs to specify the combination of input values that affect the desired output value.

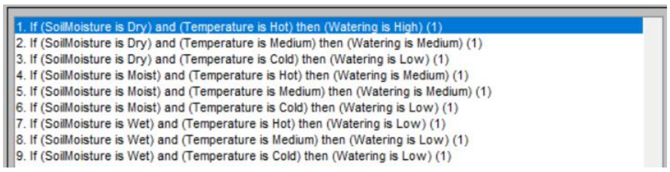

Figure 4. Rules

Fuzzy rules are formed based on the desired preferences in the system. In **Table 3**, which is presented below, the rules are represented. There are three parameters for the soil moisture input: dry, moist, and wet, while the temperature input has three parameter values: hot, medium, and cold. Thus, a total of nine fuzzy rules are generated.

Table 3. Fuzzy Rule

No	Soil Moisture	Temperature	Watering
1	Dry	Hot	High
2	Dry	Medium	Medium
3	Dry	Cold	Low
4	Moist	Hot	Medium
5	Moist	Medium	Medium
6	Moist	Cold	Low
7	Wet	Hot	Low
8	Wet	Medium	Low
9	Wet	Cold	Low

In this case, farmers often face dry soil conditions. So, the application of the rule used is, "If the soil moisture is dry and the temperature is hot, then water a lot." The application of fuzzy logic can help farmers make decisions when watering water. With this, crop yields can be increased, and the risk of water shortage can be minimized.

Membership Set

Input 1: Soil Moisture (Dry)

Figure 5 is the input data on soil moisture, with three parameters: dry, moist, and wet. The input of soil moisture helps in understanding the soil condition on which further watering and maintenance decisions are based.

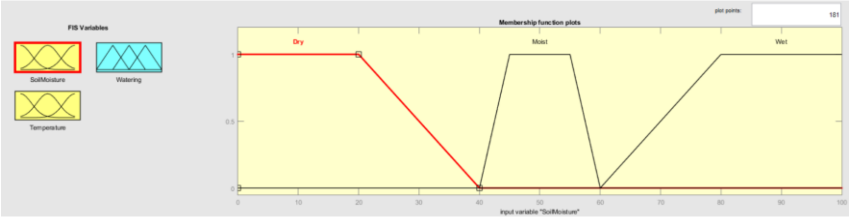

Figure 5. Membership function Moisture

Before starting, note that the x value in the soil moisture input is 30 on the right side. The right membership degree can be calculated for the next step using the predefined value.

$x = 30\ on\ the$ **(right side)**

$$\frac{d-x}{c-x} = \frac{40-30}{40-20} = \frac{10}{20} = \mathbf{0,5}$$

Membership degree $\rightarrow$ $\mathbf{0,5}$

The degree of membership for soil moisture 0.5 indicates that the soil moisture condition is in dry moisture.

Input 2: Temperature (Hot)

Figure 6 is the input data related to temperature, with three temperature conditions: hot, medium, and cold. The temperature input provides valuable information to understand the temperature levels that affect the watering and maintenance needs of the plants.

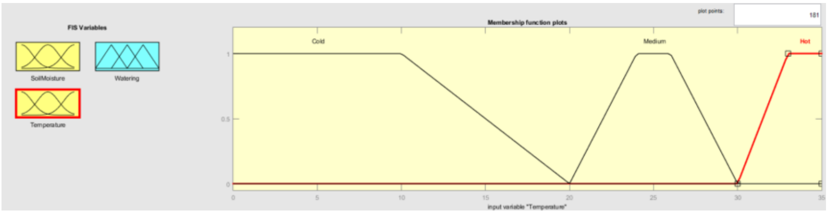

Figure 6. Membership function Temperature

$x = 33\ on\ the$ **(left side)**

Membership degree $\rightarrow$ **1**

A membership degree of 1 on the right side indicates that the temperature reaches the highest value in the hot membership set.

This case study uses the first rule of the Fuzzy Rule Base with AND logic operation. Then, the minimum value of the input membership degree is searched as follows:

$\propto 1 = \min(\mu(x)Dry[30] \cap (\mu(y)Hot[33])$

$\propto 1 = \min\ (0,5\ ; 1)$

$\propto 1 = 0,5$

Output: Watering (High)

Figure 7 is an output related to watering, with three parameters: low, medium, and high. The previously measured environmental conditions show how much water will be delivered to the rice fields.

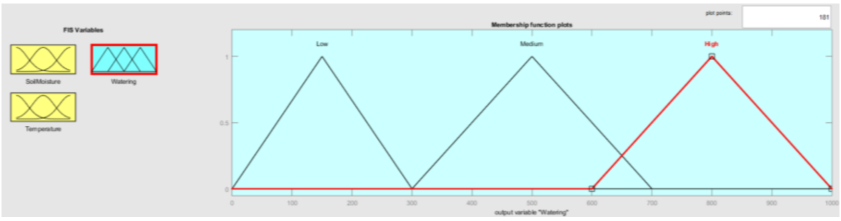

Figure 7. Membership function Watering

In this step, the formulas for a triangle's left and right sides are used to calculate the correct values. The formulas take into account the predefined parameters to get the correct result.

Left Side Output:

$$\propto \ = \frac{x1 - a}{b - a}$$

$$0{,}5 \ = \frac{x1 - 600}{800 - 600}$$

$$0{,}5 \ = \frac{x1 - 600}{200} \rightarrow 0{,}5.200 = x1 - 600$$

$$100 = x1 - 6000 \ \rightarrow 100 + 600 = x1$$

$$\boldsymbol{x1 = 700}$$

Using the membership function on the left side of the output, the membership degree value is 0.5, with the resulting intersection point of $x1$ = 700.

Right Side Output:

$$\propto \ = \frac{c - x2}{c - b}$$

$$0{,}5 \ = \frac{1000 - x2}{1000 - 800}$$

$$0{,}5 \ = \frac{1000 - x2}{200} \rightarrow 0{,}5.200 = 1000.x2$$

$$100 = 1000 - x2 \ \rightarrow x2 = 1000 - 100$$

$$\boldsymbol{x2 = 900}$$

Using the membership function on the right side of the output, the membership degree value is 0.5, with the resulting intersection point being $x2$= 900.

Composition of Output Values:

Figure 8 provides a visual representation of the output value composition. This figure will provide a better understanding of the relative proportions of the different levels of output produced in a process.

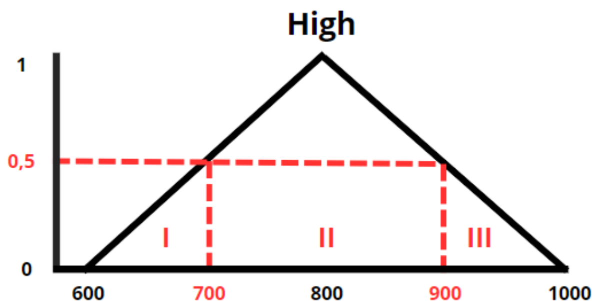

Figure 8. Composition of Output Values

After establishing the range of values and the equation for each interval, determine the corresponding membership level within each range.

$$x < 600 = 0$$

$$x > 1000 = 0$$

$$600 < x < 700 \ = \frac{x - a}{b - a} = \frac{x - 600}{800 - 600} = \frac{\boldsymbol{x - 600}}{\boldsymbol{200}} = \boldsymbol{0{,}005x - 3}$$

$700 < x < 900 = \mathbf{0,5}$

$$900 < x < 1000 \; = \frac{c-x}{c-b} = \frac{1000-x}{1000-800} = \frac{\mathbf{1000-x}}{\mathbf{200}} = \mathbf{5 - 0,005x}$$

Area:

Three different area sections have been calculated to obtain the area, each consisting of a triangle and a rectangle. By following the calculation steps, the area of each part can be determined precisely.

LD I (Triangle)

The triangular area formula, namely $\frac{a.t}{2}$, has been applied to calculate LD I. Using the specified values, the area of LD I yields a result of 25. **Figure 9** visually represents LD I, a triangular area with corresponding dimensions.

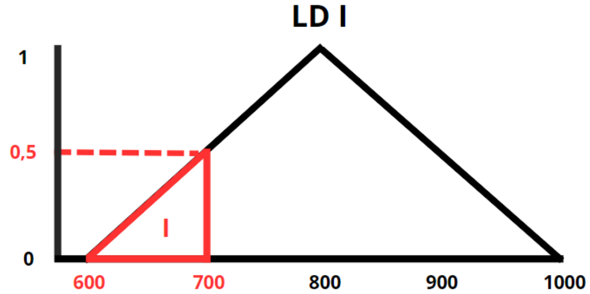

Figure 9. LD 1 (Triangle)

$$\frac{a.t}{2} = \frac{(700-600).0,5}{2} = \frac{100.0,5}{2} = \mathbf{25}$$

LD II (Rectangle)

The formula for the area of a rectangle, $p.l$, has been applied to calculate LD II. Using the specified values, the area of LD II yields a result of 100. **Figure 10** visually represents LD II, a rectangular area with corresponding dimensions.

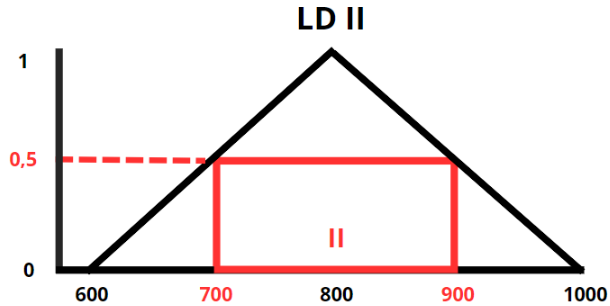

Figure 10. LD II (Rectangle)

$$p.l = (900-700).0,5 = 200.0,5 = \mathbf{100}$$

LD III (Triangle)

The triangle area formula $\frac{a.t}{2}$ has been applied to calculate LD III. Using the predetermined values, the area of LD III yields the same result as LD I. **Figure 11** then provides a visual representation of LD III, a triangular area with corresponding dimensions.

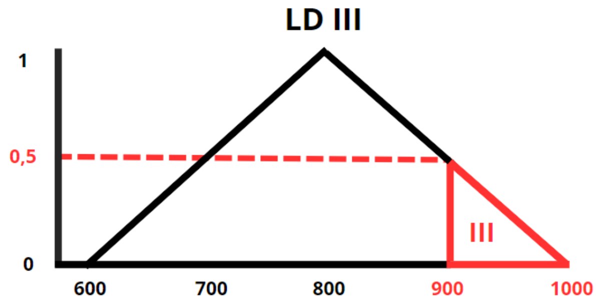

Figure 11. LD III (Triangle)

$$\frac{a.t}{2} = \frac{(1000-900).0{,}5}{2} = \frac{100.0{,}5}{2} = \frac{100.0{,}5}{2} = \mathbf{25}$$

Moment calculation

The moment calculation for fuzzy sets involves the product's integral between the fuzzy set's membership function and the variable x; it is then integrated. The result of this integral gives the value of the first moment of the fuzzy set, which represents the centre of mass or centre point of the distribution over the corresponding range of variable values.

Moment of Set I

The moment calculation for Set I involves the integration of the membership function over the variable x in the range 600 to 700.

$$\int_{600}^{700} (0{,}005x - 3)x.dx$$

$$\int_{600}^{700} (0{,}005x^2 - 3x).dx$$

$$\int_{600}^{700} \frac{0{,}005x^3}{3} - \frac{3x^2}{2}$$

Moment of Set II

The moment calculation for Set II involves the integration of the membership function over the variable x in the range 700 to 900.

$$\int_{700}^{900} (0{,}5)x.dx$$

$$\int_{700}^{900} (0{,}5x).dx$$

$$\int_{700}^{900} \frac{0{,}5x^2}{2}$$

Moment of Set III

The moment calculation for Set III involves the integration of the membership function over the variable x in the range 900 to 1000.

$$\int_{900}^{1000} (5 - 0{,}005x)x.dx$$

$$\int_{900}^{1000} (5x - 0{,}005x^2).dx$$

$$\int_{900}^{1000} \frac{5x^2}{2} - \frac{0{,}005x^3}{3}$$

Value of Set 1

In calculating the value of Set I, the expession $\frac{0{,}005x^3}{3} - \frac{3x^2}{2}$ is used to evaluate the value. The x values are replaced with 700 and 600, and the expression is evaluated for each x value. The results are then subtracted, resulting in a Set I value 16,667.

$$= \left(\frac{0{,}005.700^3}{3} - \frac{3.700^2}{2}\right) - \left(\frac{0{,}005.600^3}{3} - \frac{3.600^2}{2}\right)$$
$$= \left(\frac{0{,}005.343{,}000{,}000}{3} - \frac{3.490{,}000}{2}\right) - \left(\frac{0{,}005.216{,}000{,}000}{3} - \frac{3.360{,}000}{2}\right)$$
$$= \left(\frac{1{,}715{,}000}{3} - 735{,}000\right) - \left(\frac{1{,}080{,}000}{3} - 540{,}000\right)$$
$$= (-163333.33) - (-180000)$$
$$= -163{,}333 + 180{,}000 = \mathbf{16{,}667}$$

Value of Set II

In calculation of the value of Set II, the expression $\frac{0{,}5x^2}{2}$ The x values are replaced with 900 and 700; then, the expression is evaluated for each x value. The results are then subtracted, resulting in a Set II value of 80,000.

$$= \left(\frac{0{,}5.900^2}{2}\right) - \left(\frac{0{,}5.700^2}{2}\right)$$
$$= \left(\frac{0{,}5.810{,}000}{2}\right) - \left(\frac{0{,}5.490{,}000}{2}\right)$$
$$= \left(\frac{405{,}000}{2}\right) - \left(\frac{245{,}000}{2}\right)$$
$$= 202{,}500 - 122{,}500 = \mathbf{80{,}000}$$

Value of Set III

In calculation of the value of Set III, the expression $\frac{5x^2}{2} - \frac{0{,}005x^3}{3}$ The x values are replaced with 1000 and 900; the expression is evaluated for each x value. The results are then subtracted, resulting in a Set III value of 23,333.

$$= \left(\frac{5.1000^2}{2} - \frac{0{,}005.1000^3}{3}\right) - \left(\frac{5.900^2}{2} - \frac{0{,}005.900^3}{3}\right)$$
$$= \left(\frac{5.1000{,}000}{2} - \frac{0{,}005.1000{,}000{,}000}{3}\right) - \left(\frac{5.810{,}000}{2} - \frac{0{,}005.729{,}000{,}000}{3}\right)$$
$$= \left(\frac{5{,}000{,}000}{2} - 1{,}666{,}666\right) - \left(\frac{4{,}050{,}000}{2} - 1{,}215{,}000\right)$$
$$= 833{,}333 - 810{,}000 = \mathbf{23{,}333}$$

Defuzzification

In the defuzzification process, the main goal is to transform the system's output into a fuzzy set and a single value that is easier to understand using various methods, including the weighted average method. In this method, the weight of each value in the fuzzy set is calculated based on its membership degree. After that, the values are summed and divided by their area. The result of this calculation is a defuzzification value that represents the midpoint of the original fuzzy set.

$$\boldsymbol{Z^*} = \frac{\sum moment}{\sum Area} = \frac{16{,}667 + 80{,}000 + 23{,}333}{25 + 100 + 25} = \frac{120{,}000}{150} = \mathbf{800}$$

Figure 12 displays the data results from MATLAB used to compare with manual calculations and validate the results. By using MATLAB, it is possible to calculate parameters of interest in data analysis quickly and accurately, such as, in this case, calculating the $\boldsymbol{Z^*}$ value. Thus, MATLAB provides analysts efficiency in better examining, validating, and evaluating data.

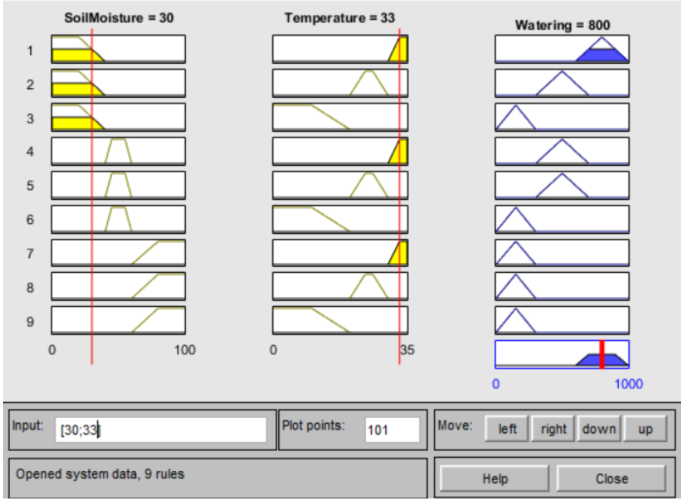

Figure 12. Matlab Calculation

The calculation results in this study show the detailed process of applying fuzzy logic to control the plant watering system. In the fuzzification stage, input data such as soil moisture and temperature are converted into fuzzy values reflecting the uncertainty level. Then, fuzzy rules are formed based on the combination of humidity and temperature inputs to determine the water that should be sprinkled into the fields. The defuzzification process is then performed to produce an output that can be used to control crop watering. The calculation results show that this system can produce values that match the measured environmental conditions, thus providing an adaptive and efficient solution for regulating plant watering. Therefore, implementing fuzzy logic in this control system can help farmers significantly increase agricultural productivity by optimizing the use of water resources.

CONCLUSION

From the results of this study, the application of Fuzzy Logic technology in controlling soil moisture levels in Arduino-based rice fields has excellent potential to improve the efficiency of water resource use and overall agricultural productivity. By accurately and adaptively considering the factors that affect soil moisture levels, the system can provide additional water to plants only when needed, thereby reducing water wastage and increasing crop yields. Integrating Arduino technology, sensors, and motor controllers is critical in creating an automated and efficient irrigation system, helping farmers better manage crop watering and increase crop yields. As a result, this research positively contributes to the development of sustainable agricultural technology.

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