An automatic irrigation system for plants using fuzzy logic controller considering volumetric water content

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Abstract. An automatic irrigation system have an important role in today agriculture sector. Currently, automatic irrigation systems which can irrigate and supply plants with desired level and amount of water required for normal plant growth are not available. Furthermore, the classical method using on-off controller is inefficient due to results in loss of energy and productivity. Thus, an efficient automatic irrigation system with fuzzy logic controller is proposed to estimate the amount of water level using the irrigation model, soil type and type of plant. This paper presents a solution for irrigation system for plants using fuzzy logic controller using MATLAB Simulink. To indicate the effectiveness of the proposed method, on-off controller method is also applied for validation purpose.

1. Introduction
The irrigation system is a very important to make sure that the plants can grow in a better environment. Plant normally obtain the water from the soil but not every soil is rich with water. This is due to the soil moisture which depends on the topography, location and weather. This characteristics of the land effect the amount of water that a plant can extract from the soil. There is soil which lack of water and not suitable for planting. Therefore, an efficient irrigation system is essential to distribute water to the plant in effective way for optimal plant life with optimal use of water. Irrigation system also provides a better and cheaper way to supply water to the soil. Malaysia receives an annual average rainfall of more than 2500 mm, mainly due to the Southwest and Northeast monsoons [1]. The country is therefore rich in water resources compared to other regions of the world. Unfortunately, the water is not stored in the soil for a long time because the water will evaporate into the air eventually or flow into the river.

2. Irrigation Parameters
In order to determine the irrigation process, the parameters need to be considered are height and depth of roots, type of soil and plant, soil’s saltiness and water [2]. Moisture of soil can be identified using volumetric sensor where it measures the amount of water in the soil. Therefore, volumetric water content (VWC) is used as the input to the automatic irrigation system. VWC is the ratio of the unit volume of water to unit volume of soil [3]. As the VWC increased, the amount of water inside the soil is increased.

Other factor such as Gravimetric Water Content (GWC) which is the ratio of water weight to soil weight is also need to be considered. The VWC can be obtained manually by converting from the GWC. To determine GWC, a soil that contain the water is taken and the weight is measured. The weight is measured again and the GWC can be calculated using Equation 1 [4]. Bulk density is the weight of the soil in the given volume. Therefore, by using the given weight, the volume can be obtained. From the
VWC, water contain inside the soil can be estimated and the best condition can be find as in Equation 2.

\[
GWC = \frac{{\text{Mass}}_{\text{soil + water}} - \text{Mass}_{\text{soil + water}}}{\text{Mass}_{\text{soil + water}}} \times 100\%
\]  

(1)

\[
VWC = GWC \times \frac{\text{BulkDensity}_{\text{soil}}}{\text{Density}_{\text{water}}} \times 100\%
\]

(2)

Parameters such as root zone is the area of soil that surrounding the root of the plant [5]. Root play an important role for the plant to gather resources such as water and mineral to make food. Thus, the root zone must contain suitable amount of water in order for plant to collect enough sources. Different plant has different root depth and root zone. The volume of root zone will affect the amount of water needed to fill the land until it reaches the desired VWC level. Bigger root zone results in more amount of water.

For different plant type, the different level of soil moisture is required. Therefore, the level of soil moisture (VWC) used, where it is considered the best for most of the plant. The VWC level also affected by the type of the soil used because different type of soil has different holding water properties. For space occupied by sand, it required 5% VWC to 10% VWC to supplied enough water to plant while the space occupied with clay required 40% to 50% VWC for it to be suitable for planting [6].

The best condition is to keep the moisture level in optimal state. The soil moisture only allows to fall into manageable allowable depletion line where it still enough to supply water for the plant. However, to obtain the best result, the soil moisture is keep at median of the optimal state where the VWC is 45% for space occupied with clay. Clay is selected because it is better soil for agriculture compare to sand. Besides that, the state such as Kedah and Perlis also has soil occupied by clay [7].

The water cycle can be separate into several process such as evaporation, condensation, precipitation, interception, infiltration, percolation, transpiration, runoff and storage [8]. However, the process that greatly effecting the irrigation system is the evaporation process due to open space and transpiration process of the plant. Evaporation is the transformation of liquid at the ground to gas at the atmospheric and it mainly cause by the solar radiation. Radiation from the sun heat and provide energy to the liquid which cause the molecules inside the liquid to move more aggressive and change from liquid to gases. Transpiration is the process that occur when the plant undergoes photosynthesis process and produce water vapor. The transpiration rate is greatly affected by the light level, hence the transpiration process occurs greatly during the day where sun light shine over. Water vapor release from the tree is evaporating into the air due to the heat and temperature of the surrounding.

Evapotranspiration is the combination of the evaporation and transpiration process [9]. Evapotranspiration (ET) is the water transverse from ground to the atmospheric which resulting in change of phase from liquid or solid to vapor [9]. Evapotranspiration must be considered in designing irrigation system because for a location with high temperature and lack of rain lead to high evapotranspiration rate.
Figure 1 shows the evapotranspiration process occurring surrounding plants. Evapotranspiration rate must be estimated in order to estimate how much water losses due to the evapotranspiration process and included in the automatic irrigation simulation. The most common approach for computing the crop evapotranspiration is reference ET approach by multiplying the crop coefficient with reference ET to find actual evapotranspiration [10]. The term evapotranspiration reference, ET$_{o}$ is introduced by the researcher in the late 1970s which is defined as the rate of evapotranspiration from a hypothetical surface with the assumption that the crop height is 0.12m, surface resistance of 70 sec/m and 0.23 albedo [11]. The estimation of ET$_{o}$ can be calculated using many methods. One of it is the Penman-Monteith method where it has been accepted as a standard method for calculating ET$_{o}$ [10]. The standardized Penman-Monteith equation for evapotranspiration reference is as in Equation 3 [10].

$$ET_o = \frac{0.408\Delta(Rm - G) + \gamma \frac{C_h}{T + 273} \nu_2(\epsilon_s - \epsilon_a)}{\Delta + \gamma(1 + C_d \nu_2)}$$

where:

- ET$_{o}$ = standardized reference crop evapotranspiration [mm d$^{-1}$],
- Rm = calculated net radiation for the standardized surface [MJ m$^{-2}$ d$^{-1}$],
- G = soil heat flux density at the soil surface [MJ m$^{-2}$ d$^{-1}$],
- T = mean daily air temperature at the 1.5 to 2.5m height [$^\circ$C],
- $\nu_2$ = mean daily wind speed at 2m height [m s$^{-1}$],
- $\epsilon_s$ = saturation vapour pressure at 1.5 to 2.5m height [kPa],
- $\epsilon_a$ = mean actual vapour pressure at 1.5 to 2.5m height [kPa],
- $\Delta$ = slope of the saturation vapour pressure-temperature curve [kPa °C$^{-1}$],
- $\gamma$ = psychometric constant [kPa °C$^{-1}$],
- Cn = numerator constant that changes with reference type and calculation time step
- Cd = denominator constant that changes with reference type and calculation time step.

To determine Evapotranspiration, the Crop coefficient approach is applied. The Crop coefficient approach incorporates Kc values which is crop coefficient value to the Evapotranspiration Reference ET$_{o}$. The crop coefficient, Kc representing the ratio of actual Evapotranspiration to the calculated evapotranspiration. The actual evapotranspiration or crop evapotranspiration is defined as in Equation 4.

$$ET_{act} = K_c \cdot ET_o$$

where:

- ET$_{o}$ = the standardized reference Evapotranspiration
- Kc = crop coefficient respective of the ET$_{o}$

There is more detailed approach of crop coefficient where the Kc is separated into two aspects which is Kcb, basal crop coefficient and Ke, soil water evaporation coefficient. This approach is called dual Kc method. The basal crop coefficient, Kcb also change depending on the growth of the plant. According to the J. L. Huntington and R. G. Allen, the Kcb during initial stage is started at low and peaking during the mid-season and drop to low again during the late session [10]. Table 1 shows the plant type and crop farm specification that was selected for this research.

| Table 1. Plant Description |
|-----------------------------|
| Plant | Tomato |
| Agriculture Area | 45m X 45m |
| Root Zone Height | 4ft or 12194m [13] |
3. Irrigation Controller

Irrigation controllers are divided into open loop controller and close loop controller. Open loop controllers may have less cost, however it does not provide an optimal solution to irrigation problem. The open-loop system is not reliable and desirable. In closed-loop controllers, it gives a feedback which requires checking the right amount of water required for irrigation process. The input, moisture sensor used to detect the soil moisture whether it is below the reference level, then the controller will actuate the system to flow the water into the soil. The condition is monitored using the sensor, then is feedback to the system which is compared with the reference. The close-loop control is preferred compare to the open-loop control because the close-loop controller has a feedback system that allow the control of the water flow to varies according to the condition of the crop field which is more reliable and efficient compare to the open-loop control. Figure 2 depicts the irrigation controller block diagram.

![Figure 2. Irrigation controller block diagram](image)

3.1. On-Off Controller

The On-Off controller (OOC) can be designed in the Simulink MATLAB model using the Stateflow function [12]. By using the Stateflow, the model can be created with sequential decision logic which normally used in supervisory control. There are two state which will represent the output such as Valve on and Valve off condition. When the Valve is off, the output of the OOC is “1” which means that the valve is 100% close. When the Valve is on, the output is “0” for the water valve is 0% close. The process is repeated continuously. The modelling of automatic irrigation system using the OOC in MATLAB Simulink is shown in Figure 3. The system is operated with 4s sample time and the OOC also operate in 4 minute by adding the 4s delay to the feedback system.

![Figure 3. Modelling Automatic Irrigation System using OOC](image)

3.2. Fuzzy Logic Controller

Fuzzy Logic Controller (FLC) is a mathematical tool that have been applied in many industrial sectors and many engineering areas. The system input is the soil moisture input block where it read the soil moisture and the value is from 0 to 100. During the first cycle, the input is sent to the FLC and the output is produced. The output from the FLC is sent to the conversion block in order to convert the valve condition into the % VWC. After that, the value is feedback into the fuzzy logic system to allow the system to input the soil moisture plus the moisture produce by the irrigation system and minus the losses due to the evapotranspiration process.
During the second cycle, the process is similar but during the summation process, the soil moisture from the first cycle % VWC is added again in order to simulate the water produce by the irrigation system. This process is succeeded by adding delay that shift the output from first cycle into second cycle summation. The simulation used the time in second to represent the minutes in real life operation. The system is set to a sample time of 4 minute with the 4-minute refresh rate of FLC. The Conversion Model used in the simulation is converting the valve opening condition into soil moisture which is % VWC. The size of water valve selected is 6 inch where the velocity of water flow in the valve is 2.71m/s [13]. The flow rate of water inside the valve is calculated using Equation 5 [14].

\[
FlowRate = \frac{\pi}{4} \times Diameter^2 \times Velocity \tag{5}
\]

From the calculation, there are 0.0494 m\(^3\) volume of water flow in each second. Then, the conversion model is inserted with the Equation 6 to the volume water into %VWC based on the volume of water flow in a second.

\[
%VWC = \frac{FlowRate(\text{Q}) \times \text{Second}}{\text{Total Soil Volume}} \times 100\% \tag{6}
\]

The root zone required is 1.2192m. \(V_{total}\) is around 2468.8 m\(^3\) which is 45m\(^2\) x 1.2192m. Formula used in the conversion model is

\[
%VWC = \frac{0.0494 \times (4 \times 60) \times \text{sec}}{2468.88} \times 100\% \times \text{unit}
\]

The 4x60 is to determine the water flow if the irrigation refresh every 4 minute as the fuzzy logic refresh rate is 4 minute and 6 water valve is used in the irrigation process. The soil evapotranspiration model is derived using the crop coefficient approach. The crop evapotranspiration can be obtained using Equation 4 as shown before. Based on R. G. Allen in [15], the value of crop coefficient, \(K_c\) for tomato plants is 1.3225. The evapotranspiration reference, \(ET_o\) is taken from a journal on Rainfall, evapotranspiration and rainfall deficit trend in Alor Setar, Malaysia which is 4.996mm/days [15]. The 4.996 is the average evapotranspiration reference for 1 day in one year. Thus \(ET_{act} = 6.6702\text{mm/days}\).

For area of 45m x45m, Volume of water loss per day = \((45 \times 45 \times 0.00607) m = 13.3796 m^3\)

Tomato root zone is 1.2192m. The total volume of ground need to be irrigated is 24688.8 m\(^3\). Hence %VWC is calculated as follows in second and minute:-

\[
%VWC = 0.5419 \% \text{per day} = 6.271990 \times 10^{-6} \text{/ second} = 3.763194 \times 10^{-4} \text{min}
\]

Figure 4 depicts the modelling design of the automatic irrigation system using the FLC.

![Figure 4. Modelling Automatic Irrigation System using FLC](image-url)
4. Results and Discussion

The aim of this research to apply fuzzy controller system for the irrigation system that will improve the efficiency of the conventional automatic irrigation system by minimizing the amount of waste water to the plant. In order to verify its performance in MATLAB Simulink, on-off controller is also used for validation purpose.

Table 2. Relationship of input and output of FLC and OOF

| Input (FLC and OOF) | Output (FLC) | Output (OOF) | Valve Condition (FLC) | Valve Condition (OOF) |
|---------------------|--------------|--------------|-----------------------|-----------------------|
| 29                  | 1            | 1            | Fully Open            | Fully Open            |
| 33                  | 0.75         | 1            | Semi Open             | Fully Open            |
| 38                  | 0.5          | 1            | Medium                | Fully Open            |
| 43                  | 0.25         | 1            | Semi Close            | Fully Open            |
| 46                  | 0            | 0            | Fully Close           | Fully Close           |

Table 2 tabulates the output of the fuzzy logic system and on-off controller system when the input is varying. The output of each controller is designed to produce 5 states of output. When the input is 29, the output of the fuzzy logic and on-off controller is 1, then the valve condition will change to fully open. As the input increases a little bit until it reaches a certain threshold, the fuzzy logic and on-off output will change from 1 until 0. Since the output of fuzzy logic is changed a little bit, the valve will also change proportional to the output of fuzzy logic which is from fully open to fully close.

It can be noticed that the output of the fuzzy logic stabilized more closely to the desired value compared to the on-off controller. Hence, the output of the irrigation system using the fuzzy logic is better compared to the using on-off controller. In addition, the result also shows that less water losses in fuzzy logic irrigation system compared to the on-off irrigation system. Figure 5 depicts the comparison between On-Off Controller and Fuzzy Logic Controller with the soil moisture desired value.

![Comparison between OOF and FLC with the desired soil moisture value](image)

Figure 5. Comparison between OOF and FLC with the desired soil moisture value

The percentage of error is calculated for both irrigation systems using the different type of controller in order to prove which controller is more efficient and accurate. Since the system is developed to fulfill the desired soil moisture which is 45% VWC, the calculation of error is to show the difference between the desired of the soil moisture and the result of the simulation which is actual soil moisture. The percentage error is calculated for the smallest error and largest error. The percentage is calculated using Equation 7.

\[
\% \text{Error} = \frac{\text{Actual} - \text{Desired}}{\text{Desired}} \times 100\% \tag{7}
\]
Table 3. The percentage error for automatic irrigation system

| Type of Controller      | Smallest Error (%) | Largest Error (%) |
|-------------------------|--------------------|-------------------|
| Fuzzy Logic Controller  | 1.5                | 2.8               |
| On-Off Controller       | 2.6                | 6.37              |

From this results shown in table 3, it can be defined that the fuzzy logic controller produces less small and largest error compare to on off controller. Moreover, it also shows that the automatic irrigation using the fuzzy logic controller has error from 1.5% to 2.8% while the automatic irrigation system using the On-Off Controller has error from 2.6% to 6.37%. Hence, the losses in automatic irrigation system using the On-Off controller is higher than fuzzy logic controller that means fuzzy logic controller is more better.

5. Conclusion
The irrigation block diagram based on-off controller and fuzzy logic controller system are built. In terms of effectiveness, an automatic irrigation system for plant using the fuzzy logic controller is more efficient in term of water usage and power consumption compared to the on-off controller. It is proven that the proposed controller is 2.275 times better than the on-off controller. The fuzzy logic proves more precise water handling that reduce the water losses. Hence, it is important to note that fuzzy logic controller also can save a lot of water, increase productivity and very easy to implement.

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