Journal of Electronic Research and Application, 2025, Volume 9, Issue 1
http://ojs.bbwpublisher.com/index.php/JERA
ISSN Online: 2208-3510
ISSN Print: 2208-3502

Intelligent Irrigation System for Agricultural Greenhouse Adaptive to Crop Growth Law

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Abstract: Greenhouse planting is a key method for increasing the yield of agricultural products in China. The Academy of Agricultural Sciences has conducted extensive research on the water requirements of greenhouse crops during various growth stages. Studies indicate that crops in the germination stage, seedling stage, and other stages of their growth cycle have different water needs. Proper irrigation can significantly enhance both crop quality and yield. To apply the Academy of Agricultural Sciences' expertise on irrigation during different growth stages to practical farming, and to avoid improper irrigation at specific stages that could reduce crop production and quality, our team has designed an intelligent irrigation system for agricultural greenhouses. This system adapts to the growth patterns of crops by establishing an irrigation model based on characteristic images of each growth stage and irrigation data provided by the Academy. Using image recognition technology, the system accurately identifies the growth stage of crops. It then employs a pre-set irrigation curve and data from humidity sensors to execute precise irrigation through a closed-loop Proportion-Integral-Differential (PID) control system. This ensures optimal water management, leading to improved crop quality and yield.

Keywords: Crop growth cycle; Image recognition; Precision irrigation

Online publication: February 12, 2025

1. Introduction

Global water management priorities are clear: water-saving irrigation has become a key aspect of agricultural modernization. The effective protection of freshwater resources and the rational development of new irrigation systems are essential for achieving sustainable agricultural development [1]. With the advancement of high technology and the increasing popularity of the Internet of Things (IoT) and 5G technology, the world is witnessing a new wave of scientific and technological progress. Countries have begun interdisciplinary research, integrating fields such as electronics, information technology, biology, and agriculture. This multi-disciplinary fusion aims to enhance the comprehensive utilization of water resources and support high-quality agricultural production and development. Precision agriculture requires a certain level of economic investment but offers significant benefits. It can achieve modernized agricultural production, improve economic returns, and reduce the workload for farmers [2,3].

Research shows that irrigation tailored to the growth stages of crops can significantly enhance their quality and yield. For instance, during the maturation stage of melons and fruits, proper irrigation is crucial. Insufficient irrigation can result in a soft texture and dry peel, while excessive irrigation may cause cracking. Therefore, adopting irrigation practices aligned with the growth stages of crops is an important trend for improving both quality and yield. Thanks to the progress of Internet of Things technology and the development of sensor technology, intelligent irrigation systems have ushered in a stage of rapid development, which provides strong support for agricultural production. The core of this project is to study the water demand at various stages of crop growth inside the greenhouse, based on the regularity of crop growth. It relies on intelligent detection and control technologies, combined with irrigation experience and the agricultural crop growth cycle, to develop a smart irrigation system that adapts to the crop growth cycle [4-5]. The system is designed to eliminate the information barrier between academia and farmers, enabling intelligent water-saving irrigation.

2. Overall scheme design of the system

The intelligent irrigation system for agricultural greenhouses, which is adaptive to the law of crop growth, mainly includes six parts: personal computer (PC) terminal (Raspberry PI), embedded intelligent control system (Arduino), high-precision visual induction system, sensor system, intelligent irrigation system, and display system, as shown in **Figure 1**.

The PC terminal of the system stores the picture library of each growth cycle of a certain crop and the water demand data of the crop in each growth cycle. The high-precision visual sensing system collects the parameters of crop growth state. The embedded intelligent control system (Arduino) collects the humidity of the crop environment of the sensing system. The intelligent irrigation system drives the water pump and solenoid valve for irrigation. The display system displays the collected crop image and the stored crop image, the humidity curve of the crop growth environment, and the pre-set humidity curve of the crop.

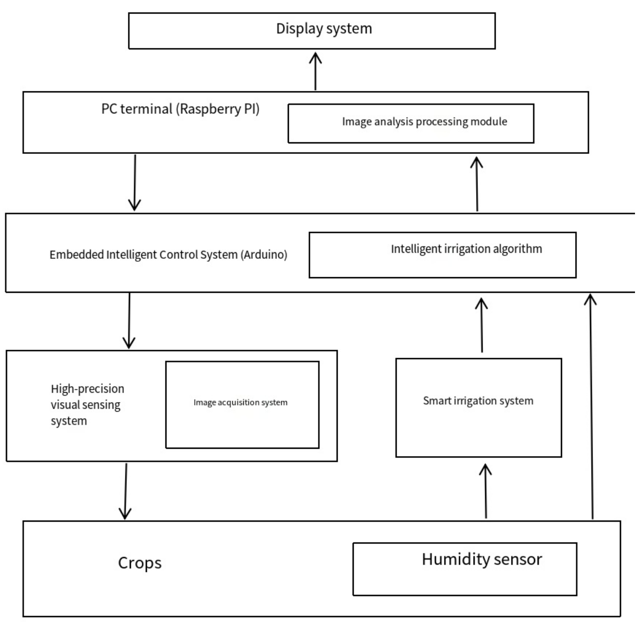

Figure 1. Overall scheme design

3. System control model establishment

The system uses Raspberry PI to store the image database of specific crops in different growth stages and the corresponding water demand data. The high-precision visual sensing system is responsible for capturing the growth image of the crop and comparing it with the stored image to determine the growth stage of the crop and determine its water requirement at that stage. Then, the embedded intelligent control system (Arduino) will collect the environmental humidity data of crops and the water demand data to compare and analyze. Through the intelligent irrigation system, the pump and solenoid valve are controlled for precise irrigation, as shown in **Figure 2**, to achieve the effect of saving water, increasing yield, and improving crop quality. The specific modeling process is as follows.

3.1. Establishment of data platform

(1) In the agricultural bureau or field, the system can confirm the characteristics of crops at each growth stage through image input. When the image sensor regularly collects images, the system compares them with known characteristics. If the similarity of the characteristics is 70% or higher, the system determines the crop's corresponding growth stage.

(2) Input the water data required for each crop during its theoretical growth week into the system platform, which then performs irrigation based on this data. The platform also adjusts irrigation adaptively by comparing the crop's humidity, as collected by the humidity sensor.

Users can choose the appropriate irrigation method according to the local actual situation and the situation of planting crops.

3.2. Irrigation decision-making mode

(1) Firstly, irrigation is carried out intelligently according to the rules of crop growth set by the system.

(2) However, when ordinary farmers perceive that there is a problem with irrigation crops according to the irrigation data, the system irrigation can be stopped. When the relevant agricultural technicians or according to the actual level of crops, the system irrigation water curve can be adjusted and the irrigation can be carried out according to the new law.

(3) The system is equipped with an alarm function. If the humidity falls outside the optimal range for the crops, or if a system component is damaged, the system will stop working and trigger an alarm.

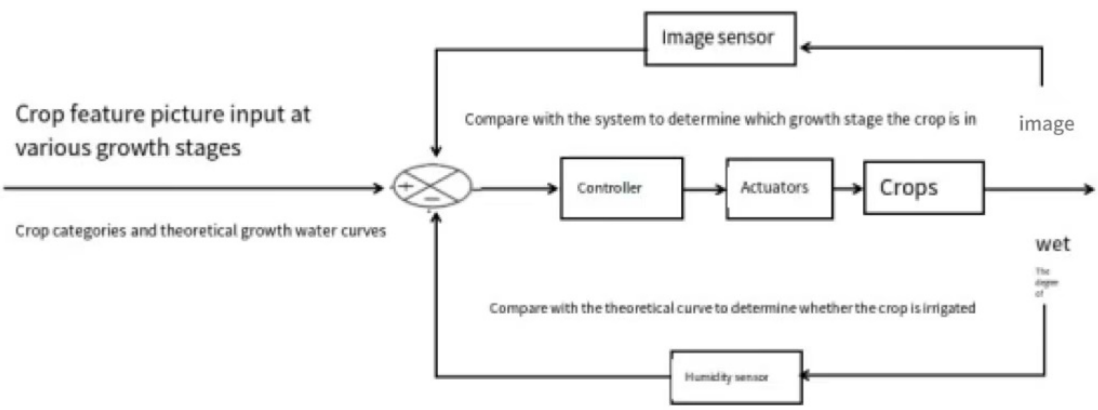

Figure 2. System control model

4. Software design

The Kingview software design control interface, including crop growth cycle judgment, moisture detection, alarm, etc., is shown in **Figure 3**.

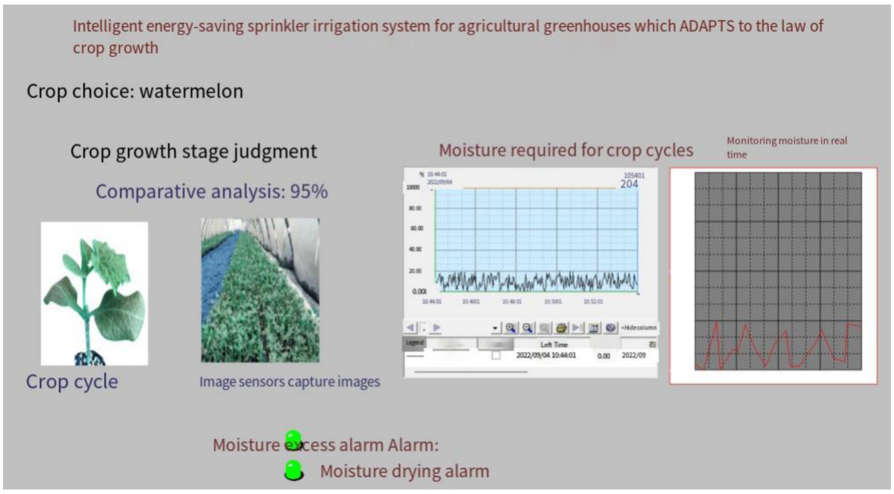

Figure 3. Software host computer

5. System operation

Farmers can select the type of crops to be planted in the greenhouse through the system, as shown in the interface diagram. The system performs irrigation based on the required moisture levels at each stage of crop growth (as displayed on the right side of the interface). The curve next to it represents the actual humidity curve of the crop, monitored in real-time by the humidity sensor. The system adjusts irrigation based on a comparison and analysis of these two data sets.

On the left side of the interface is the system used to determine the crop's growth stage. The left portion displays characteristic photos provided by the Academy of Agricultural Sciences and experienced farmers for each growth stage, while the right portion shows photos of the greenhouse collected regularly by the image collector. The system analyzes the similarity between the two sets of images to determine whether the crops have entered the next growth stage and adjust irrigation accordingly.

It is important to note that each crop has a theoretical growth stage time frame, so the image sensor only collects data on the days corresponding to crop transitions, rather than in real-time. Most of the time, the sensor is in standby mode, operating at low power or no power.

6. Image sensing technology and image processing

In the process of research on high-precision visual sensing technology, we used a 3-megapixel industrial-grade CCD camera to collect crop growth data. The camera was fixed on a tripod, and through the accurate measurement scale method and the distance between the target crop, to ensure that monitoring of crop growth can be sustained accurately. Image data is collected through wireless network transmission to the monitoring software, where the software analyzes and processes the image information to predict crop growth [6,7].

In the field of high-precision visual sensing technology, the fuzzy clustering image segmentation algorithm is used in the image segmentation process to achieve accurate division of crop images. In the process of image segmentation, the linear iterative clustering algorithm is used to generate the superpixel regions of the image. Subsequently, the feature vectors within these regions are compared to find similar vectors. By applying the fuzzy clustering mean, the segmented image regions are effectively combined, to improve the segmentation accuracy of the target region of the crop image and the efficiency of image segmentation. In the initial stage of image segmentation, the crop image is first subdivided into superpixel regions, and then the feature vector is extracted, and the fuzzy clustering algorithm is used to merge the regions to achieve accurate segmentation of the graphics. The fuzzy clustering algorithm combines a fuzzy set with the principle of the clustering algorithm, by minimizing the objective function to obtain the optimal solution and ensure the accurate segmentation of the target area [8,9]. **Figure 4** shows the application of the fuzzy clustering algorithm in the process of image segmentation.

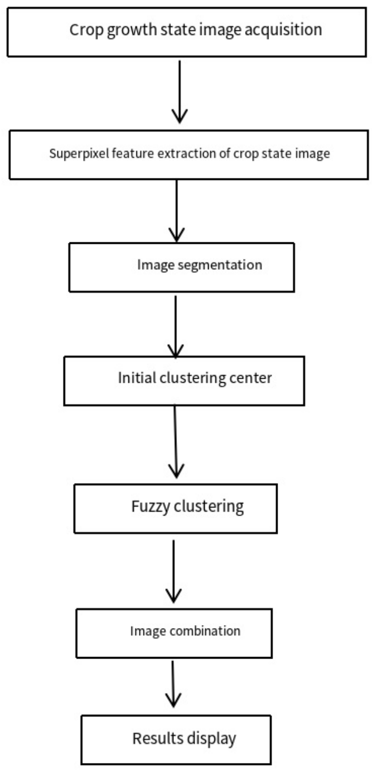

Figure 4. Flow chart of fuzzy clustering algorithm in image segmentation

The minimum objective function can be expressed as $J_m = \sum_{i=1}^{N}\sum_{j=1}^{c} u_{ji}{}^{m} d^2(w_{i,}, v_j)$

Where N represents the total number of pixels, c represents the number of clusters, m is a positive number, w_i is the gray value of the i-th pixel [10], v_j is the gray value of the cluster center in the JTH class, $d(wi,vj)$ represents the Euclidean distance between samples w_i and v_j, which is $\|w\text{-}_i V_j\|$.

When performing statistical analysis of crop image characteristics, we use pixel-based statistical methods and domain coding algorithms to reduce the number of iterations and time complexity [11–13]. First, we apply differential processing to the red (R) and green (G) components of the crop image to identify the starting point of the connected area. Next, the initial pixels in the connected region are evaluated, and a normalization process is applied to the three neighboring pixels. Finally, by iterating through all the pixels in the image, the statistical analysis of image characteristics is completed. These features are then used as input parameters to predict the crop growth status .

7. Build and test the model

The intelligent irrigation system for agricultural greenhouses [14], designed to adapt to the growth patterns of crops, features a lightweight modular design and includes three-dimensional diagram modeling and physical prototype production.

In the testing phase, we first developed a 3D map of the intelligent irrigation system design and its physical model. By adopting a lightweight and modular structure, the system can adaptively adjust to the growth patterns of crops, enabling precision irrigation. Next, field tests were conducted to verify the system's performance and reliability.

During the tests, we performed a detailed analysis of crop growth cycles to determine the optimal timing and frequency for irrigation. By collecting and analyzing crop image feature data, the system monitored the growth status of crops in real-time and automatically adjusted the irrigation plan accordingly. Additionally, we evaluated the system's response time and accuracy to ensure it meets practical application requirements [15].

After a series of tests and optimizations, we observed that the intelligent irrigation system significantly improved crop yield and quality while reducing water waste. Ultimately, the system demonstrated robust performance in practical applications, providing strong technical support for agricultural production.

Figure 5. 3D model

Figure 6. Physical model

8. Conclusion

The system bridges the information gap between the Academy of Agricultural Sciences and farmers, enabling farmers to directly apply scientific methods to the cultivation of greenhouse crops. The system, which is adaptive to crop growth patterns, enables precision irrigation. When soil moisture content does not meet crop growth requirements, the system aims to achieve high-quality, high-yield crop production. After implementation, the irrigation system is expected to increase crop yields by approximately 10% compared to current methods, while water savings can reach 3% to 6%.

The soil moisture measurement error of the system is within 3% to 8%. The control system employs PID control, maintaining a comparison error with the water requirements of crops within 3% to 10%. The system is designed to be flexible, with crop irrigation data configured through user software, eliminating the need for hardware replacement. This reduces costs by approximately 6%.

To further enhance the performance of the intelligent irrigation system, we plan to incorporate advanced technologies in future iterations. Specifically, we aim to integrate artificial intelligence (AI) algorithms to optimize irrigation decision-making processes for more precise water management. Additionally, the system will utilize IoT technology to monitor and adjust farmland environmental parameters in real-time, further improving crop growth efficiency and yield.

This system can serve as a foundation for the integration of water and fertilizer or pesticide irrigation. By adding appropriate water-fertilizer modulation or pesticide modulation systems, it will be possible to achieve integrated water and fertilizer irrigation as well as adaptive intelligent pesticide irrigation.

Disclosure statement

The authors declare no conflict of interest.

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