A Fuzzy Logic Controller for Greenhouse Temperature Regulation System Based on Edge Computing

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Abstract. Temperature and humidity are important factors affecting the growth of greenhouse crops. Reasonable temperature and humidity control can save energy and increase crop yields. This paper proposes a temperature controller based on fuzzy logic theory and applies it to smart greenhouses through edge computing. Temperature and humidity dynamic model and fuzzy logic controller (FLC) of the greenhouse are simulated by using the Simulink toolbox of MATLAB, and verified by comparison with the proportional integral derivative (PID) controller. The results show that in a multivariate greenhouse system, FLC is more stable than multiple PID controllers in temperature regulation of greenhouse.

Keywords: Edge computing · Fuzzy Logic Controller · PID controller · Simulink · Multivariate system

1 Introduction

Greenhouse environment regulation is an important part of modern agriculture. Constructing a semi-closed microclimate greenhouse environment can provide a controllable growth environment for crops, such as temperature, humidity, and light intensity. In [8,15], the authors show that improving the control performance of greenhouses can save energy while improving the efficiency and quality of crop production. The traditional cloud computing-based smart greenhouse control system collects greenhouse data such as temperature and humidity through sensors and other devices. In this mode, sensors need to upload all data to the cloud platform for analysis and backup, and the cloud platform sends control signaling according to the uploaded data, such as the fan settings. In [18], a cloud computing-based greenhouse is proposed to process data centrally, make data analysis and conduct decision-making. But the cloud based approach increases network latency since the data must be uploaded to the cloud platform and the network in the greenhouse widely use low-bandwidth wireless network

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such as Zigbee. In [7,14], deploying edge computing in the greenhouse, data can be processed and uploaded to the cloud platform in real-time at edge devices. The users can view and monitor the greenhouse environment status in real-time. The edge computing-based smart greenhouse can realize real-time data processing, reduce network delays and improve data processing efficiency.

In addition, since the greenhouse system is a nonlinear, hysteresis, and multivariable strong-coupling system, the control system deployed at the edge can accurately control environmental variables such as temperature and humidity. The PID control system is a commonly used temperature and humidity control system at present, but due to the strong coupling of the internal environmental variables of the greenhouse system, the PID control system is often difficult to complete the accurate control of the temperature. Therefore, a control system based on FLC that does not need to establish an accurate mathematical model can apply expert experience and play a very important role in a greenhouse control system. FLC has proven to be a successful control approach to many complex nonlinear systems or even nonanalytic systems. It has been suggested as an alternative approach to conventional control techniques in many cases [9].

In this paper, we propose a fuzzy logic based temperature controller for smart greenhouses based on edge computing. The controller can be installed at edge devices, to control the sunshade system, ventilation-wet curtain system, and heating system. We implement a smart greenhouse system by installing the controller on Pi devices where data collection and processing are conducted by Raspberry Pi with multiple sensors at the edge. Raspberry Pi devices upload data to Thingsboard IoT platform for data monitoring and analysis in real-time. We also use Simulink to construct a dynamic greenhouse model of temperature and humidity, and compare the performance of PID controller and FLC in this model.

2 System Structure

As shown in Fig. 1, this system consists of four layers: perception layer, device layer, network layer, and platform & application layer.

Perception Layer. The perception layer is mainly composed of temperature and humidity sensors, light sensors, flame sensors, buzzers, fans, wet curtains, and so on. Considering the factors such as anti-interference, reliability, stability, economy, the sensor uses air temperature and humidity sensor DHT11, light sensor BH1750, flame sensor YG1006. These devices are connected to the Raspberry Pi through the breadboard. The Raspberry Pi periodically collects the data from the sensors and directly controls devices such as fans based on these data. The hardware design diagram of the perception layer device connected to the Raspberry Pi is shown in Fig. 2.

Device Layer. The device layer is composed of multiple Raspberry Pis. The location of each Raspberry Pi can be planned according to the actual spatial structure of the greenhouse to achieve full coverage by deploying Raspberry Pis.

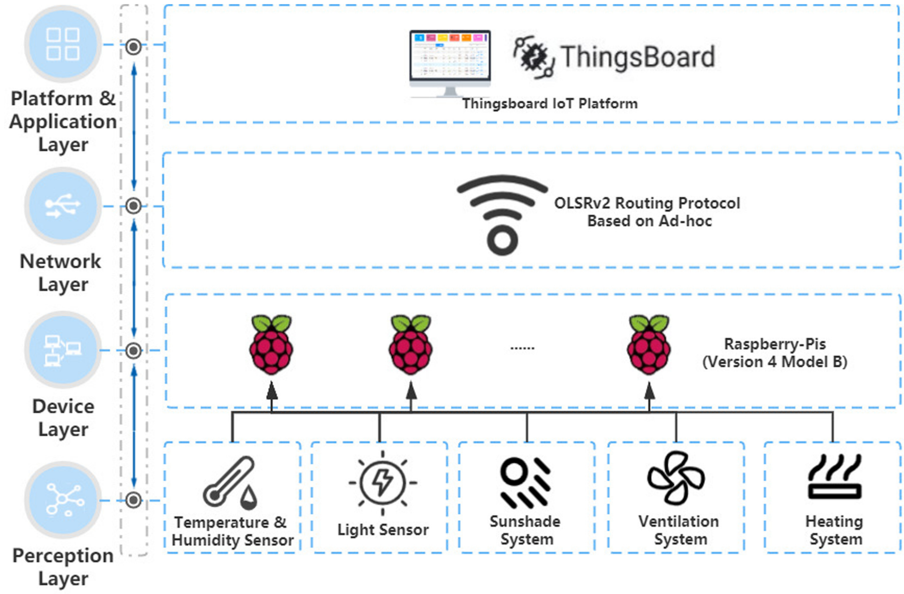

Fig. 1. Smart greenhouse system architecture.

Network Layer. The Raspberry Pi and the platform are interconnected through the ad-hoc network that configured the Optimized Link State Routing Protocol version 2 (OLSRv2) routing protocol. As shown in Fig. 3, each Raspberry Pi will find the shortest path to access the platform according to the OLSRv2 routing table. When a certain Raspberry Pi fails, the OLSRv2 will convergence and switch to another path.

Platform & Application Layer. The platform & application layer is implemented based on the Thingsboard that is an open-source IoT platform. Thingsboard can implement device registration, management, and data receiving and sending by Message Queuing Telemetry Transport (MQTT) protocol, and can configure dashboards for users.

3 Dynamic Modelling and Simulation of Greenhouse

Temperature and humidity are important environmental factors in the greenhouse. On the one hand, they are affected by environmental factors such as outdoor temperature, solar radiation, and on the other hand, they are affected by environmental control facilities such as ventilation systems in the greenhouse. Therefore, on the basis of analyzing the influence of indoor and outdoor factors on the temperature and humidity in the greenhouse, combined with the influence of sunshade system, ventilation-wet curtain system, and heating system on temperature and humidity, this paper proposes a modified dynamic greenhouse

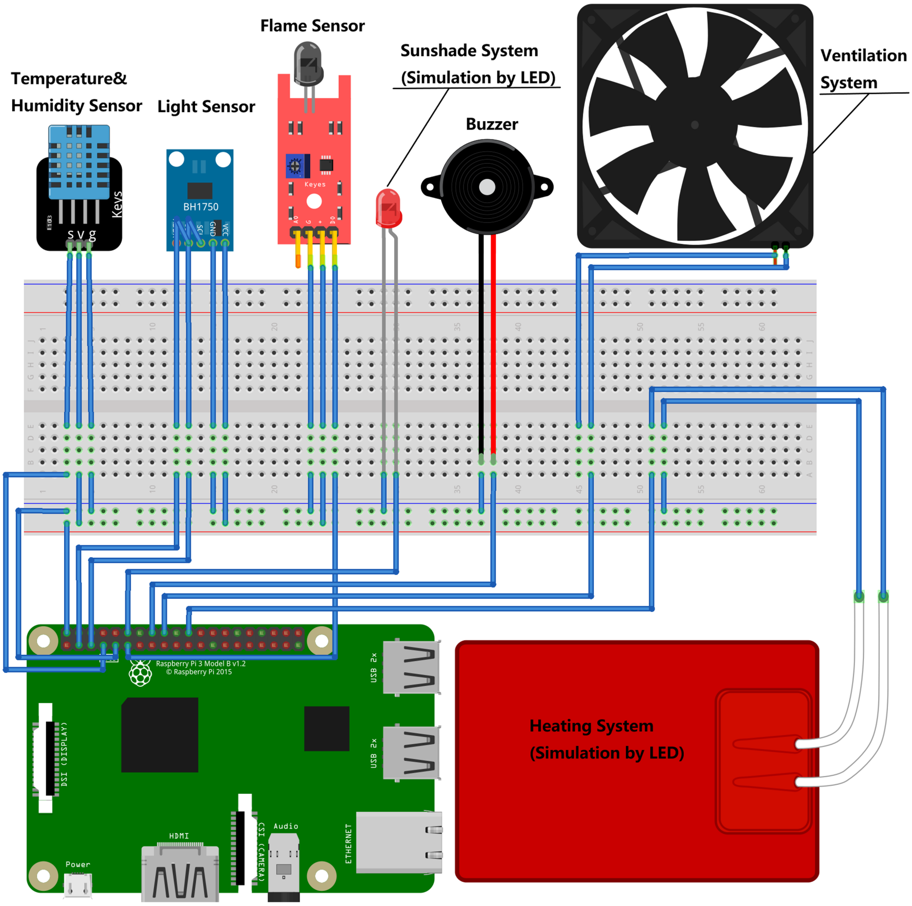

Fig. 2. Hardware design.

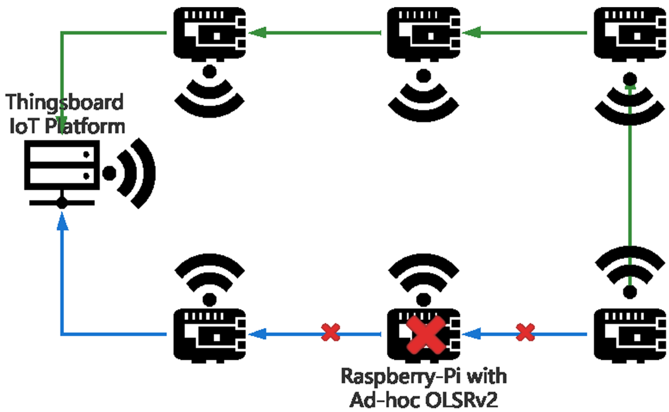

Fig. 3. OLSRv2.

model based on the existing paper, and use the Simulink for simulation and controller performance verification.

3.1 Temperature Dynamic Model

The paper [3,5,11,13,17] gives a temperature dynamic mathematical model of greenhouse based on the conservation of energy (1).

$$\Delta Q = Q_{rad} - Q_{cac} - Q_{crad} - Q_{vent} - Q_{wet} + Q_{heat} + Q_{tran} \tag{1}$$

In the formula (1), ΔQ is the change in energy in the greenhouse per unit time, Q_{rad} is the energy-absorbing from the solar radiation, Q_{cac} is the convection and conduction heat transfer rate, and Q_{crad} is the longwave radiation absorbed by the greenhouse, Q_{vent} is heat loss through the ventilation system, Q_{wet} is heat loss through the wet curtain, Q_{heat} is the heat increased through the heating system, Q_{tran} is the energy needed for greenhouse crop transpiration. In order to reduce the complexity of the model, the heat exchanging with soil in the greenhouse and the energy needed for greenhouse crop transpiration are ignored. The formula (1) is further simplified to obtain the formula (2).

$$\Delta Q = Q_{rad} - Q_{cac} - Q_{crad} - Q_{vent} - Q_{wet} + Q_{heat} \tag{2}$$

$$\Delta Q = V \rho C_p \frac{\mathrm{d}T_i}{\mathrm{d}t} \tag{3}$$

In the formula (2) (3), the unit of Q_{rad}, Q_{cac}, Q_{crad}, Q_{vent}, Q_{wet} and Q_{heat} are all $W \cdot m^{-2}$. V is the volume of greenhouse m^3, ρ is the air density $(kg \cdot m^{-3})$, C_p is the specific heat capacity of the air $(J \cdot kg^{-1} \cdot m^{-3})$, T_i is the indoor temperature (K), and t is time (s), $\frac{\mathrm{d}T_i}{\mathrm{d}t}$ represents the rate of change of indoor temperature.

$$Q_{rad} = A_s I_r \tau + 0.7 A_s I_r \tag{4}$$

$$Q_{cac} = A_s K_g (T_i - T_o) \tag{5}$$

$$Q_{crad} = A_g \varepsilon_{12} \sigma (T_i^4 - T_o^4)) \tag{6}$$

$$Q_{vent} = \phi_{vent} \rho C_p (T_i - T_o) \tag{7}$$

$$Q_{wet} = \phi_{wet} \rho W (H_a - H_b) \tag{8}$$

$$Q_{heat} = A_p h_p (T_p - T_i) \tag{9}$$

Where, in the formula (4), A_s is the surface area of the greenhouse covering material (m^2), I_r is the radiation flux density outdoor $(W \cdot m^{-2})$, and τ is the light transmittance of the covering material. In the formula (5), K_g is the greenhouse cover material heat transfer coefficient $(W \cdot m^{-2} \cdot K^{-1})$, T_i is the indoor temperature (K), and T_o is the outdoor temperature (K). In the formula

(6), ε_{12} is the surface emissivity, and σ is the Stefan-Boltzman constant ($W \cdot m^{-2} \cdot K^{(4)}$). In the formula (7), ϕ_{vent} is the ventilation volume of the ventilation system ($m^3 \cdot s^{-1}$). In the formula (8), ϕ_{wet} is the ventilation rate of the wet curtain ($m^3 \cdot s^{-1}$), W is the latent heat of evaporation, T_{avg} is the average of indoor temperature, H_a is the humidity before the wet curtain (%), and H_b is the humidity after the wet curtain (%). In the formula (7), A_p is the surface area of the heating system (m^2), h_p is the heat transfer coefficient of the heating system, and T_p is the heating system temperature (K).

3.2 Humidity Dynamic Model

The paper [2,12,19] gives a humidity dynamic mathematical model of greenhouse based on the water vapor in greenhouse (10).

$$\Delta E = E_{tran} + E_{wet} - E_{vent} - E_{cond} \tag{10}$$

In the formula (10), E_{tran} is the sum of water vapor generated by crop transpiration and soil surface water evaporation, E_{wet} is the water vapor generated by the wet curtain, E_{vent} is the water vapor lost by the ventilation system, and E_{cond} is the water vapor lost by condensation on the greenhouse surface. In order to reduce the complexity of the model, as a result of the simulation time is not long, E_{tran} and E_{cond} can be ignored. The formula (10) is further simplified to obtain the formula (11).

$$\Delta E = E_{wet} - E_{vent} \tag{11}$$

$$\Delta E = h\frac{\mathrm{d}H_i}{\mathrm{d}t} \tag{12}$$

In the formula (11) (12), the unit of E_{wet} and E_{vent} are both, h is the average height of the greenhouse, H_i is the indoor humidity (%), t is the time (s), $\frac{\mathrm{d}H_i}{\mathrm{d}t}$ is the rate of change of the indoor humidity.

$$E_{wet} = \frac{\phi_{wet}\rho}{A_g} \tag{13}$$

$$E_{vent} = \frac{\phi_{vent}(H_i - H_o)}{d_s} \tag{14}$$

Where, A_g is the surface area of the greenhouse ground (m^2), H_i is the indoor humidity (%), H_o is the outdoor humidity (%), and d_s is the density of water ($kg \cdot m^{-3}$).

3.3 Simulation of Greenhouse Dynamic Temperature and Humidity Model

The greenhouse model in this paper is based on the Venlo modern greenhouse, and the greenhouse covering material is glass. Assuming that the greenhouse is equipped with a sunshade system that can cover half of the greenhouse surface, a ventilation system composed of a fan of $5\,m^3 \cdot s^{-1}$, and a steam heating system with a surface area of $80\,m^2$. The value of each parameter is shown in the Table 1.

Table 1. Parameters of greenhouse environment

Parameter	Symbol	Value
Volume of greenhouse	$\rho/kg \cdot m^{-3}$	1.2
Heat capacity of air	$C_p/J \cdot kg^{-1} \cdot m^{-3}$	1006
Radiation flux density outdoor	I_r	0.89
Covering film light transmittance	τ	0.89
Covering film heat transfer coefficient	$K_g/W \cdot m^{-2} \cdot K^{-1}$	$1.86(T_i - T_o)^{0.33}$
Surface emissivity coefficients	ε_{12}	$(\varepsilon_1^{-1} + \varepsilon_1^{-1} - 1)^{-1}$
Air emissivity coefficients	ε_1	0.9
Cladding material emissivity coefficients	ε_2	0.9
Latent heat of evaporation	W	$2501 - 2.36T_{avg}$
Heating system heat transfer coefficient	h_p	$1.95(T_p - T_i)^{0.33}$
Stefan-Boltzman constant	σ	5.67×10^{-8}
Density of water	$d_s/kg \cdot m^{-3}$	997

The greenhouse is in a closed or semi-closed state for a long time, and the indoor temperature and humidity are affected by various indoor and outdoor environmental factors. Therefore, the dynamic model of the greenhouse is a multivariable, non-linear system, and the relationship between various variables and parameters is complicated. Using the Simulink, the formula (2) (11) is divided into several subsystems in a modular way, and then the various subsystems are combined to obtain a simulation diagram of the temperature and humidity dynamic model of the greenhouse, as shown in Fig. 4.

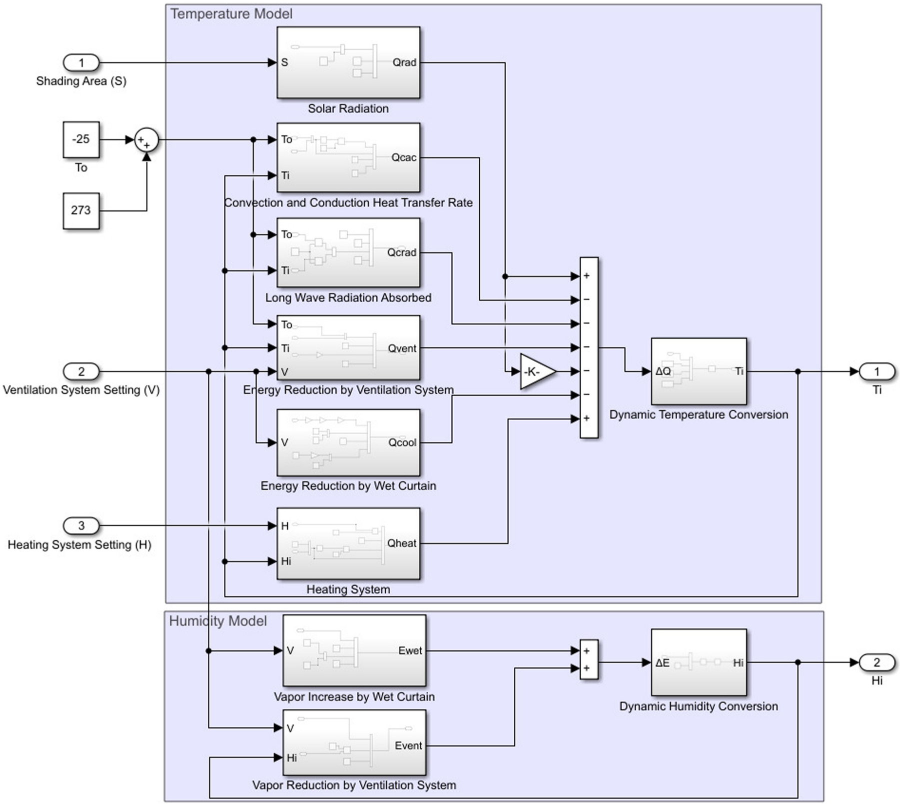

Fig. 4. Greenhouse model.

4 Fuzzy Logic Controller Design

Fuzzy Logic Controller (FLC) is based on the way of thinking of people in a dynamic environment. It abstracts the operator's experience into a series of conditional sentences and completes process control with the help of a computer. For greenhouses with nonlinear and hysteresis, as a result of FLC has less dependence on the accuracy of the greenhouse mathematical model and has good robustness, FLC is very suitable for the environmental controller of the greenhouse. Due to the greenhouse complex dynamics of the envelopment physics, the fuzzy control represents a useful tool to be applied to this type of processes [15].

This paper focuses on the temperature control of the greenhouse and chooses an optimal FLC with three inputs and three outputs.

4.1 Fuzzification

This paper chooses to control the temperature in the greenhouse. The main control methods include turning on the sunshade system and ventilation-wet curtain system to cool down in summer and turning on the heating system to warm up in winter. The three input variables are the difference between the set temperature and the current indoor temperature (T_e), the changing rate of the temperature difference (T_{ec}) (the change rate of T_e: $\frac{\mathrm{d}T_e}{\mathrm{d}t}$) and the current indoor humidity (H_i). T_e and T_{ec} are used to eliminate temperature deviation, and the addition of H_i can make the control more precise. The three output variables are sunshade system S, ventilation-wet curtain system V, and heating system H settings. The fuzzy field of the three input variables are all [−6 6], and the quantization factors K_{e1}, K_{e2} and K_{e3} of T_e, T_{ec} and H_i are 6, 10, and 6 respectively. The fuzzy field of the three output variables are all [0 6], and their quantization factors are all 1/6, that is, the output is controlled at [0 1] to achieve percentage-based control of the three controlled objects, such as the output variable of the ventilation system is 0.4, that is, its ventilation volume is 40%. By dynamically adjusting the ventilation system, heating system, and other systems, energy can be saved while meeting the growth requirements of crops. Both the input variable and the output variable select the triangular membership function, which is described by five fuzzy states of NB (Negative Big), NS (Negative Small), ZE (Zero), PS (Positive Small), and PB (Positive Big). The membership function formulas of the input variable (T_e) as an example are shown in the formula (15).

$$f(x,a,b,c) = \begin{cases} 0 & x \le a \\ \frac{x-a}{b-a} & a \le x \le b \\ \frac{c-x}{c-b} & b \le x \le c \\ 0 & c \le x \end{cases} \tag{15}$$

Where, taking variable T_e as an example, the membership functions of NB, NS, ZE, PS, and PB are respectively $f(x,-6,-6,-3)$, $f(x,-6,-3,0)$, $f(x,-3,0,3)$, $f(x,0,3,6)$ and $f(x,3,6,6)$. The membership functions of T_{ec} and H_i are consistent with T_e. The membership function image of the input variable T_e as an example is shown in Fig. 5.

It has been pointed out that the manual tuning process of production rules and membership functions is extremely time-consuming in the development of fuzzy control system [4]. So now there is a lot of work to add neural networks to FLC, and neural networks are used for automatic configuration of membership functions, etc., which can reduce workload and increase the accuracy of FLC.

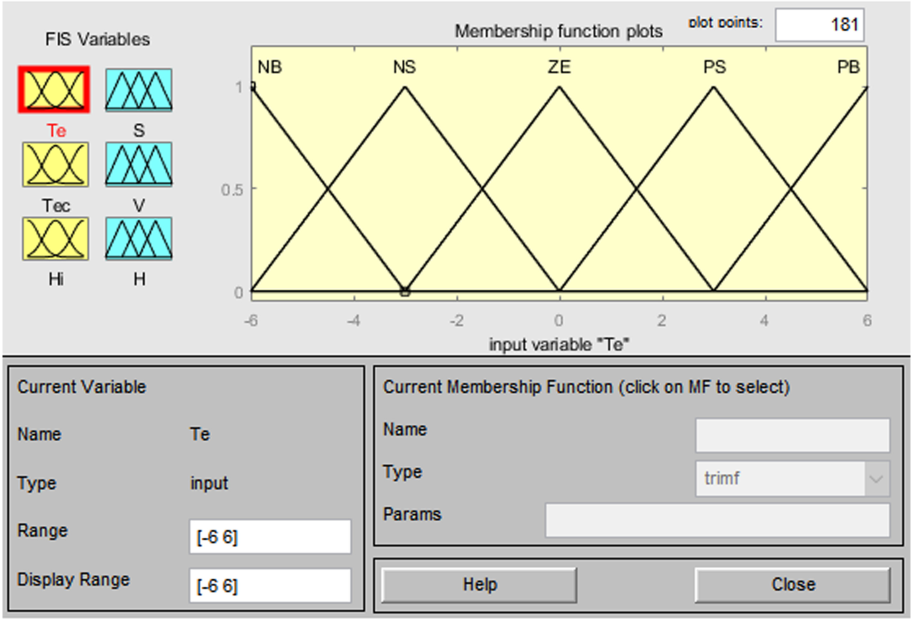

Fig. 5. Membership function.

4.2 Fuzzy Rule Base

According to the expert experience and existing papers [1,6,16], the following empirical rule base for environmental temperature control based on IF-THEN is obtained. When in summer, the heating system is closed:

- 1. IF T_e is PB, THEN S is NB, AND V is PB.
- 2. IF T_e is PS, AND T_{ec} is Negative, THEN S is NS, AND V are PS.
- 3. IF H_i is PB, THEN V needs to reduced one level.

When in winter, the wet curtain is closed and the ventilation system is in a low gear state:

- 1. IF T_e is NB, THEN S and H are NB.
- 2. IF T_e is NS, AND T_{ec} is Positive, THEN S and H are NS.
- 3. IF H_i is PB, THEN V needs to increased one level.

According to the above rules, T_e and T_{ec} can be used to eliminate the temperature difference, and the current humidity H_i can make the system controlling more precise. According to the above rules, establish a fuzzy control rule table of that three output variables, as shown in Fig. 6, 7 and 8.

1. If (temp is NB) and (tempt is NB) and (humidity is NB) then (sun is PB)(vent is NB)(heat is PB) (1)
2. If (temp is NB) and (tempt is NB) and (humidity is NS) then (sun is PB)(vent is NB)(heat is PB) (1)
3. If (temp is NB) and (tempt is NB) and (humidity is ZE) then (sun is PB)(vent is NB)(heat is PB) (1)
4. If (temp is NB) and (tempt is NB) and (humidity is PS) then (sun is PB)(vent is NB)(heat is PB) (1)
5. If (temp is NB) and (tempt is NB) and (humidity is PB) then (sun is PB)(vent is NS)(heat is PB) (1)
6. If (temp is NB) and (tempt is NS) and (humidity is NB) then (sun is PB)(vent is NB)(heat is PB) (1)
7. If (temp is NB) and (tempt is NS) and (humidity is NS) then (sun is PB)(vent is NB)(heat is PB) (1)
8. If (temp is NB) and (tempt is NS) and (humidity is ZE) then (sun is PB)(vent is NB)(heat is PB) (1)
9. If (temp is NB) and (tempt is NS) and (humidity is PS) then (sun is PB)(vent is NB)(heat is PB) (1)
10. If (temp is NB) and (tempt is NS) and (humidity is PB) then (sun is PB)(vent is NS)(heat is PB) (1)
11. If (temp is NB) and (tempt is ZE) and (humidity is NB) then (sun is PB)(vent is NB)(heat is PB) (1)
12. If (temp is NB) and (tempt is ZE) and (humidity is NS) then (sun is PB)(vent is NB)(heat is PB) (1)
13. If (temp is NB) and (tempt is ZE) and (humidity is ZE) then (sun is PB)(vent is NB)(heat is PB) (1)
14. If (temp is NB) and (tempt is ZE) and (humidity is PS) then (sun is PB)(vent is NB)(heat is PB) (1)
15. If (temp is NB) and (tempt is ZE) and (humidity is PB) then (sun is PB)(vent is NS)(heat is PB) (1)
16. If (temp is NB) and (tempt is PS) and (humidity is NB) then (sun is PB)(vent is NB)(heat is PB) (1)
17. If (temp is NB) and (tempt is PS) and (humidity is NS) then (sun is PB)(vent is NB)(heat is PB) (1)
18. If (temp is NB) and (tempt is PS) and (humidity is ZE) then (sun is PB)(vent is NB)(heat is PB) (1)
19. If (temp is NB) and (tempt is PS) and (humidity is PS) then (sun is PB)(vent is NB)(heat is PB) (1)
20. If (temp is NB) and (tempt is PS) and (humidity is PB) then (sun is PB)(vent is NS)(heat is PB) (1)
21. If (temp is NB) and (tempt is PB) and (humidity is NB) then (sun is PS)(vent is NS)(heat is PS) (1)
22. If (temp is NB) and (tempt is PB) and (humidity is NS) then (sun is PS)(vent is NS)(heat is PS) (1)
23. If (temp is NB) and (tempt is PB) and (humidity is ZE) then (sun is PS)(vent is NS)(heat is PS) (1)
24. If (temp is NB) and (tempt is PB) and (humidity is PS) then (sun is PS)(vent is NS)(heat is PS) (1)
25. If (temp is NB) and (tempt is PB) and (humidity is PB) then (sun is PS)(vent is ZE)(heat is PS) (1)
26. If (temp is NS) and (tempt is NB) and (humidity is NB) then (sun is PB)(vent is NB)(heat is PB) (1)
27. If (temp is NS) and (tempt is NB) and (humidity is NS) then (sun is PB)(vent is NB)(heat is PB) (1)
28. If (temp is NS) and (tempt is NB) and (humidity is ZE) then (sun is PB)(vent is NB)(heat is PB) (1)
29. If (temp is NS) and (tempt is NB) and (humidity is PS) then (sun is PB)(vent is NB)(heat is PB) (1)
30. If (temp is NS) and (tempt is NB) and (humidity is PB) then (sun is PB)(vent is NS)(heat is PB) (1)
31. If (temp is NS) and (tempt is NS) and (humidity is NB) then (sun is PB)(vent is NB)(heat is PB) (1)
32. If (temp is NS) and (tempt is NS) and (humidity is NS) then (sun is PB)(vent is NB)(heat is PB) (1)
33. If (temp is NS) and (tempt is NS) and (humidity is ZE) then (sun is PB)(vent is NB)(heat is PB) (1)
34. If (temp is NS) and (tempt is NS) and (humidity is PS) then (sun is PB)(vent is NB)(heat is PB) (1)
35. If (temp is NS) and (tempt is NS) and (humidity is PB) then (sun is PB)(vent is NS)(heat is PB) (1)
36. If (temp is NS) and (tempt is ZE) and (humidity is NB) then (sun is PB)(vent is NB)(heat is PB) (1)
37. If (temp is NS) and (tempt is ZE) and (humidity is NS) then (sun is PB)(vent is NB)(heat is PB) (1)
38. If (temp is NS) and (tempt is ZE) and (humidity is ZE) then (sun is PB)(vent is NB)(heat is PB) (1)
39. If (temp is NS) and (tempt is ZE) and (humidity is PS) then (sun is PB)(vent is NB)(heat is PB) (1)
40. If (temp is NS) and (tempt is ZE) and (humidity is PB) then (sun is PB)(vent is NS)(heat is PB) (1)
41. If (temp is NS) and (tempt is PS) and (humidity is NB) then (sun is PS)(vent is NS)(heat is PS) (1)
42. If (temp is NS) and (tempt is PS) and (humidity is NS) then (sun is PS)(vent is NS)(heat is PS) (1)
43. If (temp is NS) and (tempt is PS) and (humidity is ZE) then (sun is PS)(vent is NS)(heat is PS) (1)
44. If (temp is NS) and (tempt is PS) and (humidity is PS) then (sun is PS)(vent is NS)(heat is PS) (1)
45. If (temp is NS) and (tempt is PS) and (humidity is PB) then (sun is PS)(vent is ZE)(heat is PS) (1)
46. If (temp is NS) and (tempt is PB) and (humidity is NB) then (sun is PS)(vent is NS)(heat is PS) (1)
47. If (temp is NS) and (tempt is PB) and (humidity is NS) then (sun is PS)(vent is NS)(heat is PS) (1)
48. If (temp is NS) and (tempt is PB) and (humidity is ZE) then (sun is PS)(vent is NS)(heat is PS) (1)
49. If (temp is NS) and (tempt is PB) and (humidity is PS) then (sun is PS)(vent is NS)(heat is PS) (1)
50. If (temp is NS) and (tempt is PB) and (humidity is PB) then (sun is PS)(vent is ZE)(heat is PS) (1)

Fig. 6. Fuzzy rule base 1.

51. If (temp is ZE) and (tempt is NB) and (humidity is NB) then (sun is PS)(vent is NS)(heat is PS) (1)
52. If (temp is ZE) and (tempt is NB) and (humidity is NS) then (sun is PS)(vent is NS)(heat is PS) (1)
53. If (temp is ZE) and (tempt is NB) and (humidity is ZE) then (sun is PS)(vent is NS)(heat is PS) (1)
54. If (temp is ZE) and (tempt is NB) and (humidity is PS) then (sun is PS)(vent is NS)(heat is PS) (1)
55. If (temp is ZE) and (tempt is NB) and (humidity is PB) then (sun is PS)(vent is ZE)(heat is PS) (1)
56. If (temp is ZE) and (tempt is NS) and (humidity is NB) then (sun is PS)(vent is NS)(heat is PS) (1)
57. If (temp is ZE) and (tempt is NS) and (humidity is NS) then (sun is PS)(vent is NS)(heat is PS) (1)
58. If (temp is ZE) and (tempt is NS) and (humidity is ZE) then (sun is PS)(vent is NS)(heat is PS) (1)
59. If (temp is ZE) and (tempt is NS) and (humidity is PS) then (sun is PS)(vent is NS)(heat is PS) (1)
60. If (temp is ZE) and (tempt is NS) and (humidity is PB) then (sun is PS)(vent is ZE)(heat is PS) (1)
61. If (temp is ZE) and (tempt is ZE) and (humidity is NB) then (sun is ZE)(vent is ZE)(heat is ZE) (1)
62. If (temp is ZE) and (tempt is ZE) and (humidity is NS) then (sun is ZE)(vent is ZE)(heat is ZE) (1)
63. If (temp is ZE) and (tempt is ZE) and (humidity is ZE) then (sun is ZE)(vent is ZE)(heat is ZE) (1)
64. If (temp is ZE) and (tempt is ZE) and (humidity is PS) then (sun is ZE)(vent is ZE)(heat is ZE) (1)
65. If (temp is ZE) and (tempt is ZE) and (humidity is PB) then (sun is ZE)(vent is PS)(heat is ZE) (1)
66. If (temp is ZE) and (tempt is PS) and (humidity is NB) then (sun is ZE)(vent is ZE)(heat is ZE) (1)
67. If (temp is ZE) and (tempt is PS) and (humidity is NS) then (sun is ZE)(vent is ZE)(heat is ZE) (1)
68. If (temp is ZE) and (tempt is PS) and (humidity is ZE) then (sun is ZE)(vent is ZE)(heat is ZE) (1)
69. If (temp is ZE) and (tempt is PS) and (humidity is PS) then (sun is ZE)(vent is ZE)(heat is ZE) (1)
70. If (temp is ZE) and (tempt is PS) and (humidity is PB) then (sun is ZE)(vent is PS)(heat is ZE) (1)
71. If (temp is ZE) and (tempt is PB) and (humidity is NB) then (sun is NS)(vent is PS)(heat is NS) (1)
72. If (temp is ZE) and (tempt is PB) and (humidity is NS) then (sun is NS)(vent is PS)(heat is NS) (1)
73. If (temp is ZE) and (tempt is PB) and (humidity is ZE) then (sun is NS)(vent is PS)(heat is NS) (1)
74. If (temp is ZE) and (tempt is PB) and (humidity is PS) then (sun is NS)(vent is PS)(heat is NS) (1)
75. If (temp is ZE) and (tempt is PB) and (humidity is PB) then (sun is NS)(vent is PB)(heat is NS) (1)
76. If (temp is PS) and (tempt is NB) and (humidity is NB) then (sun is ZE)(vent is ZE)(heat is ZE) (1)
77. If (temp is PS) and (tempt is NB) and (humidity is NS) then (sun is ZE)(vent is ZE)(heat is ZE) (1)
78. If (temp is PS) and (tempt is NB) and (humidity is ZE) then (sun is ZE)(vent is ZE)(heat is ZE) (1)
79. If (temp is PS) and (tempt is NB) and (humidity is PS) then (sun is ZE)(vent is ZE)(heat is ZE) (1)
80. If (temp is PS) and (tempt is NB) and (humidity is PB) then (sun is ZE)(vent is NS)(heat is ZE) (1)
81. If (temp is PS) and (tempt is NS) and (humidity is NB) then (sun is ZE)(vent is ZE)(heat is ZE) (1)
82. If (temp is PS) and (tempt is NS) and (humidity is NS) then (sun is ZE)(vent is ZE)(heat is ZE) (1)
83. If (temp is PS) and (tempt is NS) and (humidity is ZE) then (sun is ZE)(vent is ZE)(heat is ZE) (1)
84. If (temp is PS) and (tempt is NS) and (humidity is PS) then (sun is ZE)(vent is ZE)(heat is ZE) (1)
85. If (temp is PS) and (tempt is NS) and (humidity is PB) then (sun is ZE)(vent is NS)(heat is ZE) (1)
86. If (temp is PS) and (tempt is ZE) and (humidity is NB) then (sun is NS)(vent is PS)(heat is NS) (1)
87. If (temp is PS) and (tempt is ZE) and (humidity is NS) then (sun is NS)(vent is PS)(heat is NS) (1)
88. If (temp is PS) and (tempt is ZE) and (humidity is ZE) then (sun is NS)(vent is PS)(heat is NS) (1)
89. If (temp is PS) and (tempt is ZE) and (humidity is PS) then (sun is NS)(vent is PS)(heat is NS) (1)
90. If (temp is PS) and (tempt is ZE) and (humidity is PB) then (sun is NS)(vent is ZE)(heat is NS) (1)
91. If (temp is PS) and (tempt is PS) and (humidity is NB) then (sun is NS)(vent is PS)(heat is NS) (1)
92. If (temp is PS) and (tempt is PS) and (humidity is NS) then (sun is NS)(vent is PS)(heat is NS) (1)
93. If (temp is PS) and (tempt is PS) and (humidity is ZE) then (sun is NS)(vent is PS)(heat is NS) (1)
94. If (temp is PS) and (tempt is PS) and (humidity is PS) then (sun is NS)(vent is PS)(heat is NS) (1)
95. If (temp is PS) and (tempt is PS) and (humidity is PB) then (sun is NS)(vent is ZE)(heat is NS) (1)
96. If (temp is PS) and (tempt is PB) and (humidity is NB) then (sun is NS)(vent is PS)(heat is NS) (1)
97. If (temp is PS) and (tempt is PB) and (humidity is NS) then (sun is NS)(vent is PS)(heat is NS) (1)
98. If (temp is PS) and (tempt is PB) and (humidity is ZE) then (sun is NS)(vent is PS)(heat is NS) (1)
99. If (temp is PS) and (tempt is PB) and (humidity is PS) then (sun is NS)(vent is PS)(heat is NS) (1)
100. If (temp is PS) and (tempt is PB) and (humidity is PB) then (sun is NS)(vent is ZE)(heat is NS) (1)

Fig. 7. Fuzzy rule base 2.

4.3 Defuzzification

This FLC adopts the minimum method to implement the AND operator, adopts the maximum method to implement the OR operator, adopts the Mamdani fuzzy inference method, and adopts the Center of Gravity (COG) method as the defuzzification method.

4.4 Fuzzy Logic Controller Simulation

Based on the above theory, use the Simulink toolbox to establish a fuzzy controller as shown in the Fig. 9.

5 Edge Computing on Greenhouse System

Finally, install the program for reading and uploading sensor data and FLC simulated by Simulink according to the previous paper on the Raspberry-Pis (version 4 model B) to realize the control of fans and other devices at the edge. This FLC is built by Skfuzzy in the Python library and installed on the Raspberry Pi. It can effectively maintain suitable temperature and humidity and

101. If (temp is PB) and (tempt is NB) and (humidity is NB) then (sun is NS)(vent is PS)(heat is NS) (1)
102. If (temp is PB) and (tempt is NB) and (humidity is NS) then (sun is NS)(vent is PS)(heat is NS) (1)
103. If (temp is PB) and (tempt is NB) and (humidity is ZE) then (sun is NS)(vent is PS)(heat is NS) (1)
104. If (temp is PB) and (tempt is NB) and (humidity is PS) then (sun is NS)(vent is PS)(heat is NS) (1)
105. If (temp is PB) and (tempt is NB) and (humidity is PB) then (sun is NS)(vent is ZE)(heat is NS) (1)
106. If (temp is PB) and (tempt is NS) and (humidity is NB) then (sun is NB)(vent is PB)(heat is NB) (1)
107. If (temp is PB) and (tempt is NS) and (humidity is NS) then (sun is NB)(vent is PB)(heat is NB) (1)
108. If (temp is PB) and (tempt is NS) and (humidity is ZE) then (sun is NB)(vent is PB)(heat is NB) (1)
109. If (temp is PB) and (tempt is NS) and (humidity is PS) then (sun is NB)(vent is PB)(heat is NB) (1)
110. If (temp is PB) and (tempt is NS) and (humidity is PB) then (sun is NB)(vent is PS)(heat is NB) (1)
111. If (temp is PB) and (tempt is ZE) and (humidity is NB) then (sun is NB)(vent is PB)(heat is NB) (1)
112. If (temp is PB) and (tempt is ZE) and (humidity is NS) then (sun is NB)(vent is PB)(heat is NB) (1)
113. If (temp is PB) and (tempt is ZE) and (humidity is ZE) then (sun is NB)(vent is PB)(heat is NB) (1)
114. If (temp is PB) and (tempt is ZE) and (humidity is PS) then (sun is NB)(vent is PB)(heat is NB) (1)
115. If (temp is PB) and (tempt is ZE) and (humidity is PB) then (sun is NB)(vent is PS)(heat is NB) (1)
116. If (temp is PB) and (tempt is PS) and (humidity is NB) then (sun is NB)(vent is PB)(heat is NB) (1)
117. If (temp is PB) and (tempt is PS) and (humidity is NS) then (sun is NB)(vent is PB)(heat is NB) (1)
118. If (temp is PB) and (tempt is PS) and (humidity is ZE) then (sun is NB)(vent is PB)(heat is NB) (1)
119. If (temp is PB) and (tempt is PS) and (humidity is PS) then (sun is NB)(vent is PB)(heat is NB) (1)
120. If (temp is PB) and (tempt is PS) and (humidity is PB) then (sun is NB)(vent is PS)(heat is NB) (1)
121. If (temp is PB) and (tempt is PB) and (humidity is NB) then (sun is NB)(vent is PB)(heat is NB) (1)
122. If (temp is PB) and (tempt is PB) and (humidity is NS) then (sun is NB)(vent is PB)(heat is NB) (1)
123. If (temp is PB) and (tempt is PB) and (humidity is ZE) then (sun is NB)(vent is PB)(heat is NB) (1)
124. If (temp is PB) and (tempt is PB) and (humidity is PS) then (sun is NB)(vent is PB)(heat is NB) (1)
125. If (temp is PB) and (tempt is PB) and (humidity is PB) then (sun is NB)(vent is PS)(heat is NB) (1)

Fig. 8. Fuzzy rule base 3.

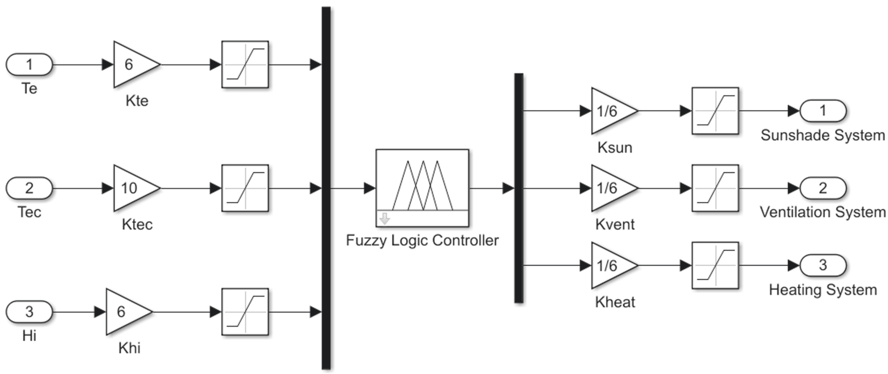

Fig. 9. Fuzzy logic controller.

other greenhouse environment factors. The Raspberry-Pi will directly make policy decisions based on the sensor data, and upload the sensor data and decision data to the IoT platform in real-time, as shown in the Fig. 10, users can view the environmental status and settings of controlled devices of the greenhouse in real-time.

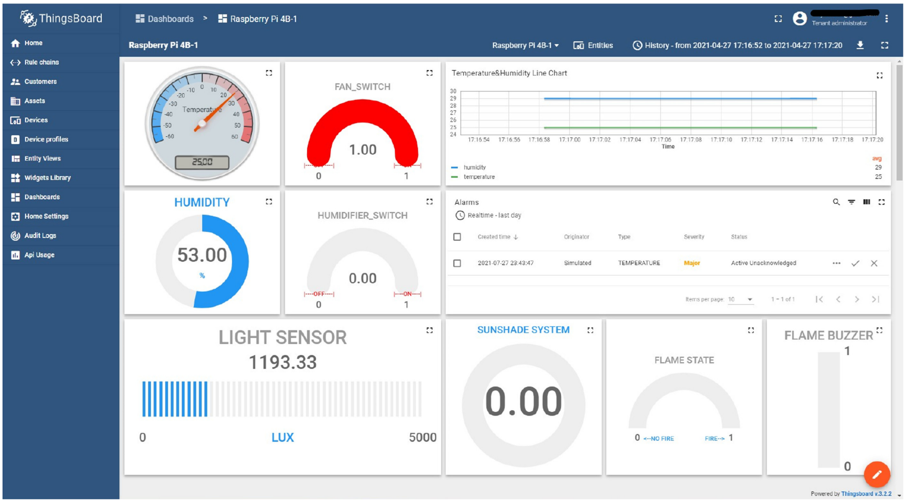

Fig. 10. Thingsboard dashboard.

The edge computing on greenhouse system integrates computing, storage, and network functions into edge devices such as Raspberry-Pi. It is actually a distributed deployment form that can effectively reduce network latency and is very suitable for low-bandwidth and low-power scenarios such as greenhouses. In the paper [10], deploying edge computing in the irrigation system of the greenhouse, and the edge node can realize a stable AI irrigation system that is not affected by communication disconnection and delay. Therefore, a smart greenhouse system based on edge computing can effectively construct a stable and efficient smart greenhouse.

6 Results and Analysis

The greenhouse dynamic model based on Simulink has been established, and the greenhouse dynamic model with FLC is as shown in the Fig. 11.

In order to verify the advantages of fuzzy control theory in this MIMO greenhouse system, as shown in the Fig. 11, PID control is introduced into the greenhouse dynamic model for comparison. Since there are three control variables: sunshade system, ventilation system, and heating system, three PID controllers are established to control these three systems respectively. The values of K_p, K_i, and K_d of the three PID controllers are adjusted separately based on the control variable method, as shown in the Table 2.

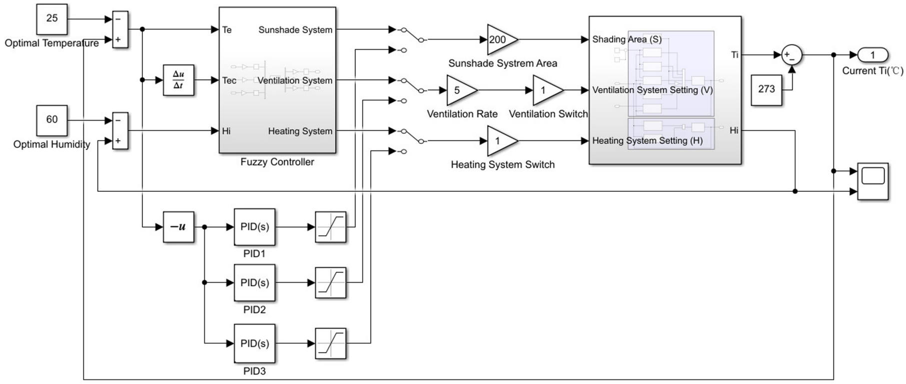

Fig. 11. Greenhouse dynamic model With FLC and PID controller.

Table 2. An example table of the current state

	K_p	K_i	K_d
Sunshade system	0.1	0.00000001	0
Ventilation system	−0.007	0.0000087	0.0000017
Heating system	0.008	0.00002	0.000004

Simulating the greenhouse state in summer and winter respectively, and the simulation time is two hours. As a result of the outdoor temperature does not change much within two hours, the outdoor temperature in summer and winter are set to fixed values of 30 °C and −25 °C, respectively. In summer, the temperature images of FLC and PID controller are shown in the Fig. 12.

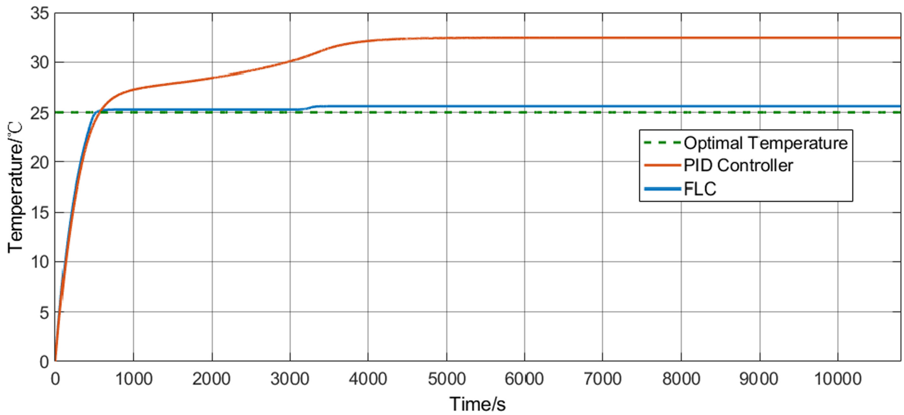

Fig. 12. FLC and PID controller in summer.

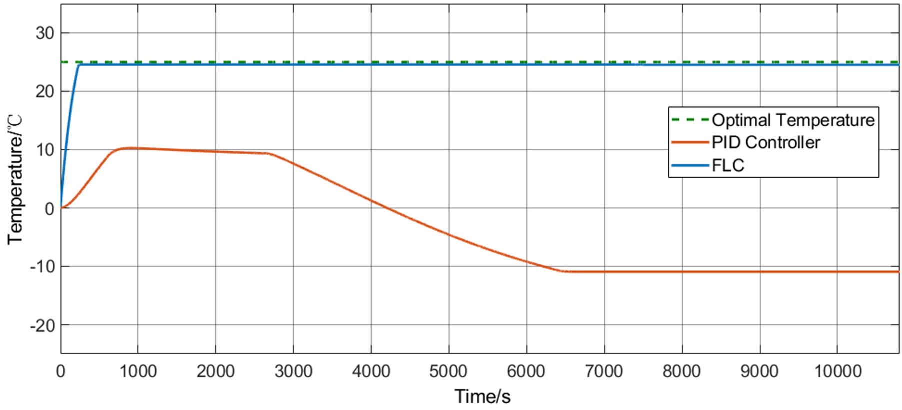

Fig. 13. FLC and PID controller in winter.

In winter, the temperature images of FLC and PID controller are shown in the Fig. 13.

7 Conclusion and Future Work

Since the greenhouse is a non-linear, hysteresis, and multi-variable coupling system, it is difficult to directly control environmental factors such as temperature and humidity. This paper proposes a FLC for smart greenhouse. We deploy FLC and PID controllers in the greenhouse separately, combine three input variables (T_e, T_{ec}, H_i), and compare the performance of these two controllers in different seasons. The results show that in a greenhouse system with multiple inputs and multiple outputs, FLC is more stable for temperature control, and the PID controller needs to completely decouple the relationship between environmental variables and configure the three factors of K_p, K_i, K_d to have a stable control output. Finally, the FLC is successfully deployed on the Raspberry-Pi through the Skfuzzy module to achieve control function based on edge computing, and the Thingsboard is used as the IoT platform to monitor the greenhouse environment, and the deployment of the greenhouse temperature FLC based on edge computing in the greenhouse is completed.

Future work is mainly on the allocation strategy of control tasks. When the number of edge nodes increases and the traffic congestion occurs, whether the control strategy can be implemented at the edge and the cloud at the same time is the focus of the next step.

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