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A RIDING FUZZY CONTROL SYSTEM FOR A MOUNTAIN AGRICULTURAL ROBOT

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Abstract- A fuzzy control system was designed to command driving directions for a mountain agriculture robot. First, a fuzzy control system program was developed based on the scheme of the robot driving control system. Then, the core part of the system--the fuzzy controller--was designed. Finally, a system model was created and a simulation test was conducted through the application of the Fuzzy Toolbox in MATLAB and SIMULINK. The results showed that the system is effective.

Index terms: mountain, agricultural robot, fuzzy control, simulation.

I. INTRODUCTION

Due to labor shortages in agricultural production worldwide, automation, informatization and intellectualization have become the inevitable trend for agricultural production and agricultural machinery. With the development of computer technology and information acquisition and processing technologies, research into agricultural robots has become more serious and gradually has become an important area of application for intelligent control technology and other high-technologies [1]. Agricultural production has the special challenges of varied working objects, great labor intensity and a complicated working environment. Currently, it is extremely difficult to perform field weeding, thinning and harvesting with only mechanization and automation. Perhaps the only way to overcome these problems is to rely on intelligent agricultural machinery, which has the ability to study and think as a human being. Such a product is named an agricultural robot [2]. Since several French researchers developed an autonomous walking robot for farm use by using field navigation technology in 1981, agricultural robots have developed rapidly. In this paper, a fuzzy control system is proposed that aims to perform riding control of a mountain agriculture robot. The system is capable of analyzing and processing navigational information from the visual subsystem; simultaneously, the system implements the corresponding decision tasks. The robot is able to complete a driving task by operating an actuator [8-9].

The structure of the paper is as follows. Section I introduces the development of the robot, analyzes the necessity of developing mountain agriculture robots, and lays out the general content of the article. Section II describes the control basis and method of determining driving directions. Section III analyzes the motion control strategy. In Section IV, the fuzzy controller is designed. In Section V, we put forward the model and simulation of the fuzzy control system. Finally, conclusions are presented in Section VI.

II. CONTROL BASIS AND METHOD OF DRIVING DIRECTIONS

a. Robot driving direction and navigation parameters

When a mountain agriculture robot conducts rotary tillage in an orchard, the proper direction to drive is along the center line between two rows of fruit trees *O-O* or lines parallel to it. Therefore, the center line *O-O* (or its parallels) can be regarded as the robot's navigation path.

The relationship between the center line of the navigation path and the robot's position is shown in figure 1. The world coordinate system $X_wY_wZ_wO_w$ was established, and the projection point of the robot's vision sensors on the ground was defined as the world coordinate system origin O_w. X_w, Y_w and Z_w were, respectively, defined as the vertical direction to the center line, the direction parallel to the heading of robot and the direction perpendicular and upward to the ground.

The posture of the robot, which is measured relative to the center line of the navigational path, was described by using two parameters: the heading declination ψ_w, which is defined as the angle between the positive of the Z_w axis and the navigation path centerline, and the transverse deviation ρ, which is defined as the distance between the origin O_w of the world coordinate system and the centerline of the navigation path. According to the two navigation parameters, we can first determine the riding condition between the rows of fruit trees and then analyze and plan for the task by using the corresponding driving control method, which is output as a corresponding control signal to drive actuator movement.

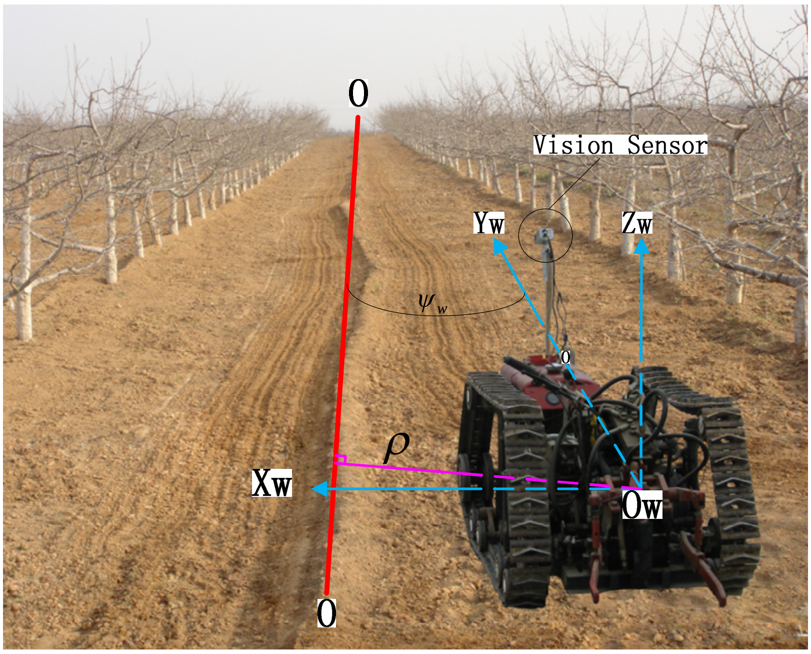


Figure 1. The relative position between the robot and navigation path

b. The choice of control basis and method

The purpose of creating a control strategy to determine driving directions is to guarantee that the agricultural robot will drive and work in accordance with the predetermined operation route (the navigation tracking path) and will travel by a corresponding offset when faced with obstacles or road changes. Driving direction control is based on the information extracted from navigation path identification; namely, the robot should determine its driving directions and steering amplitude according to the lateral deviation and heading angle declination as shown in figure 1. Specifically, an operating agricultural robot requires adjustments to the direction of travel in two situations. In the first situation, the robot is offset a distance ρ relative to the center line of the path, and in the other, a deviation ψ_w occurs between the midline direction of the identified navigation path and the travel direction of the robot. While establishing a model for a mountain agriculture robot's motion was rather complex, we chose lateral deviation ρ and heading declination ψ_w as the two reference parameters. The two parameters were found to be random and non-linear in a normal robot motion process, so it was difficult to describe the precise mathematical model (e.g., using differential equations). After comparing the practical situation of our robot and the characteristics of a fuzzy control system, we decided to use fuzzy control as the movement control method [10-11].

c. Determination of the control scheme

The input parameter variables of a fuzzy control system that come from the visual subsystem specifically refer to lateral deviation ρ and heading declination ψ_w. After processing by the control system, an output signal is obtained and sent to both the left and right sides of the oil passage controller in the hydraulic system. This control enables the crawler actions and allows the robot to travel and work along the navigation path as shown in figure 2 (the core part of the diagram is the fuzzy control system).

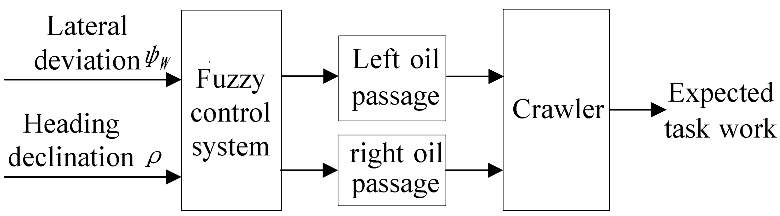


Figure 2. The block diagram of the control system

III. MOTION CONTROL STRATEGY

a. The fuzzy control system

The so-called fuzzy control method is an overall system control method based on fuzzy object models that uses a fuzzy controller to conduct approximate reasoning [12-13]. The basic concept is to use the machine to control the system as a human being would. The corresponding fuzzy theory can effectively address measurement uncertainties, parameter uncertainties and other fuzzy characteristics of the entire system. Based on the theory, the control methods can measure and describe the required data better and make use of artificial but useful empirical information [14].

After summarizing the behavioral process, which is under the guidance of experience based on the corresponding rules, a controller can be designed to convert fuzzy language into numerical output by using basic fuzzy theory, fuzzy linguistic variables and fuzzy logical reasoning. Then, we can use the processor to achieve these specific control rules and control the object automatically rather than by manual operation [15]. The design of a fuzzy control system is shown in a diagram in figure 3.

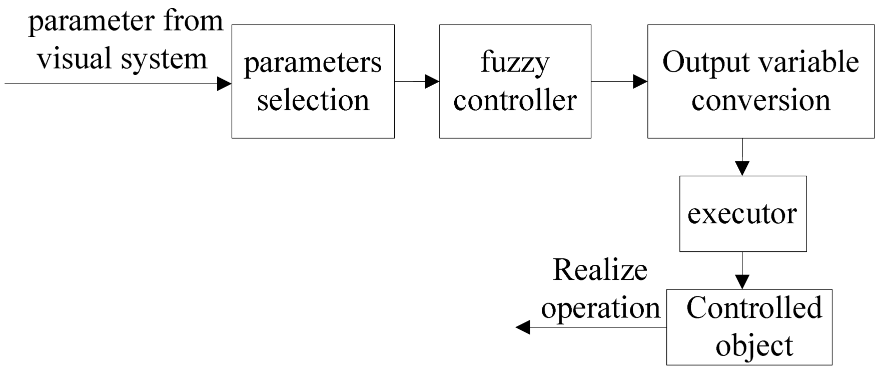


Figure 3. Block diagram of a fuzzy control system

A fuzzy control system generally has the following components[16]: Fuzzy Controller -- we chose the microcontroller in the system according to actual needs such as characteristics of the available system machine, microcontroller and SBC; Input / Output Interface Device -- the fuzzy control system receives path navigation parameters from the upper-level visual subsystem through the input / output interface device and transports the output variable to the implementing agency after Digital/Analog conversion or Level transformation; and generalized objects including the implementing agencies and the controlled object. In this paper, the generalized objects are hydraulic actuators and driving devices.

b. Determination of fuzzy control system program

To reasonably design the fuzzy control system, the effect of the two input variable parameters ρ and ψ_w on agricultural robot operations must be analyzed. All possible situations in which the robot may deviate from the navigation path in the simulation are shown in figure 4. The black line represents the target feature line (the line of fruit trees or green protection along the band edge) and the red line represents the center line between rows of fruit trees. The offset distance ρ is negative to the left side of Z_w and positive to the right side, and the navigation angle is negative to the left direction and positive to the right bias over the range of [-90 °, 90 °].

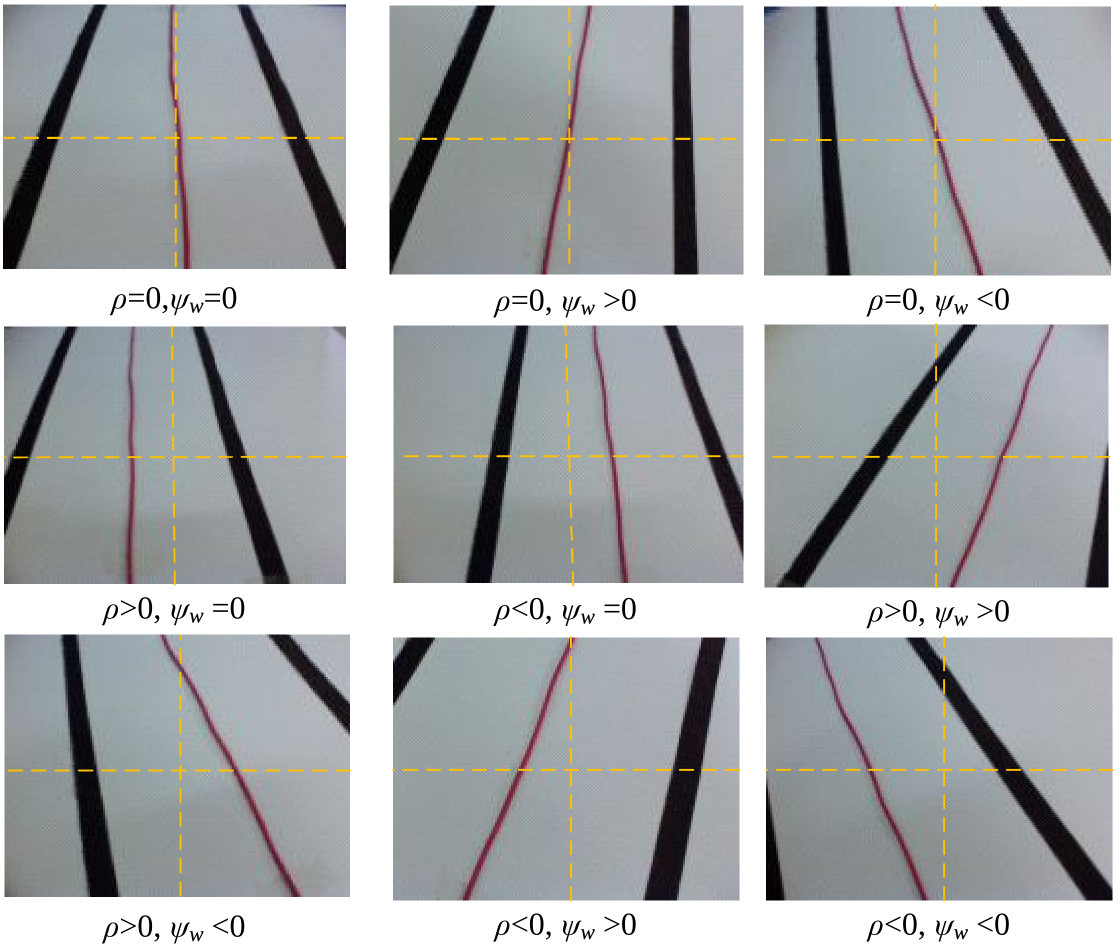


Figure 4. All possible simulated driving situations for the orchard robot

From figure 4, we can conclude that when $\psi_w = 0$ and $\rho = 0$, the robot walks straight; for $\psi_w \in (-90°, 0]$ and $\rho \neq 0$, the robot turns right; and for $\psi_w \in [-90°, 0)$ and $\rho \neq 0$, the robot turns left. As the travel speed of the robot in the practical study had been set in advance, the value of the parameters in the figure can be used on a pre-determined basis; namely, these parameters can preliminarily dictate whether the job machine continues to travel or steers. However, the machine is not yet able to judge the steering amplitude, and we need to introduce fuzzy control to solve this problem.

Through the above analysis, the specific program design of a fuzzy control system can be drawn (figure 5). The system preliminarily judges two variables—lateral deviation ρ and heading declination ψ_w —and the fuzzy control will be skipped when the variables fail to meet the above steering conditions. If the variables match the above conditions, the fuzzy controller will make decisions based on the input variables (offset distance and navigation angle) and gauge the steering direction and magnitude of the motion before execution. Next, the control signal is generated after the system determines the execution time of the steering change according to the amplitude. The system outputs a control signal to the electromagnetic valve driving device to achieve navigation path tracking operations.

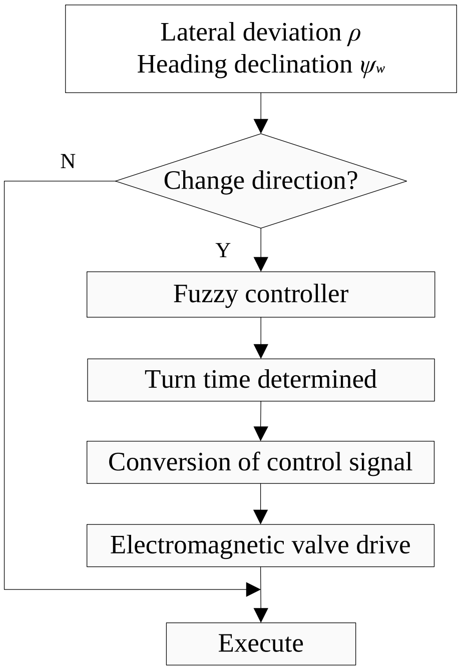


Figure 5. Block diagram of the decision tree for a fuzzy control system.

IV. FUZZY CONTROLLER DESIGN

A fuzzy controller can also be called a vague language controller because its internal control rules are based on linguistic control rules that are described by related fuzzy conditional statements. The fuzzy controller is an important part of the fuzzy control system, and its structural design and adaptability will directly impact on the performance of the entire system. The basic block diagram of a fuzzy controller is shown in figure 6.

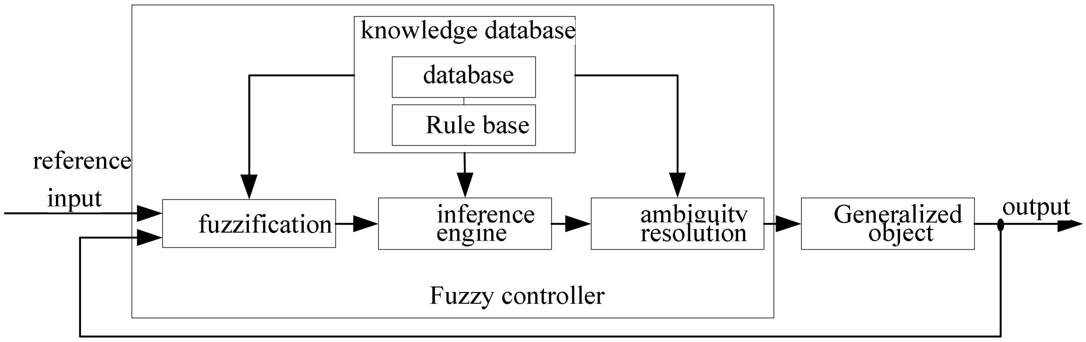


Figure 6. Fuzzy controller

a. Design steps for a fuzzy controller

The design of a fuzzy controller includes the following items:

(1) Determine the values of input and output parameters of the fuzzy controller. Specifically, choose the number and features of the control variables;
(2) Determine the domain range of the fuzzy controller's input and output variables and select relevant values for parameters such as scale factor and quantization factor;
(3) Determine the fuzzy method variables before applying the control principle and the output variable defuzzification method applied after the control principle;
(4) Design the control rules to control input variables either by generating a consulting table or establishing a function; and
(5) Describe the sampling time of the fuzzy control algorithm.

b. The specific design of the fuzzy controller

b.i Determine the properties of fuzzy controller variables

Determination of the input and output variables of the fuzzy controller is the core structural design task to create a fuzzy controller. The number of input variables is known as the fuzzy control dimension. While they have faster reaction speeds and greater practical applicability, the single-input/single-output fuzzy control structure is often incomplete and inaccurate and has poor dynamic performance. The accuracy of the fuzzy controller can be improved by adding dimensions at a cost of complicating the design; the difficulty of creating a control algorithm will increase as well. Currently, two-dimensional fuzzy controllers are widely used, and they will also be used in this paper. The input variables are the navigation path parameters (lateral deviation ρ and heading declination ψ_w) extracted from the visual image recognition subsystem while the output is a single variable.

The single output variable from the fuzzy controller will command the operating machine to turn left, turn right or continue forward. The corresponding output variable was defined as u:

for u < 0, the operating machine turns left;

for u > 0, the operating machine turns right; and

for u = 0, the operating machine remains in the original state to continue moving forward.

b.ii Fuzzification of the variables and determination of the membership function

The variable fuzzy process translates variables expressed in digital form into a fuzzy rating represented by the Universal Description lexicon. Generally, the three words "big", "middle" and "small" are used to describe the condition of the fuzzy controller’s input and output variables. Using excessively descriptive vocabulary is convenient to define the fuzzy control rules, but it also increases the complexity. Conversely, using a too small vocabulary causes the scalars to become rough in turn. Combining these analyses, using the three descriptor words and considering the changes in both positive and negative directions, we selected seven vocabularies to describe the fuzzy state [17]: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (O), Positive Small (PS), Positive Medium (PM) and Positive Big (PB).

Each input and output variable was fuzzed as follows:

(1) Navigation angle ψ_w

Based on figure 3, the navigation angle ψ_w extracted in this article was based in image plane coordinates with the y-axis as a reference. A left offset was negative while a right offset was positive, and the basic theory domain range was [-90 °, 90 °]. The descriptive language was divided into seven levels {NB, NM, NS, O, PS, PM, PB} with quantization levels {-3, -2, -1, 0, 1, 2, 3}, and the quantization factor K_{ψ_w} =3/90.

(2) Lateral deviation ρ

Similar to declination angle in image plane coordinates, we used the center of the x-axis as the central point where a left offset was negative while a right offset was positive. The width of the machine was 840 *mm* and the fruit tree line spacing was presumed to be *M mm*. Thus, the maximum offset distance was $\rho = 0.5(M-840)$, and the basic domain range was $[-0.5(M-840), 0.5(M-840)]$. If *M* = 2000 *mm*, the domain is [-580, 580]. The space was divided into seven classes but was not evenly distributed: the quantization levels were{-5,-4,-3,-2,-1,0,1,2,3,4,5}, and the descriptive language was divided into seven levels{NB(-5), NM(-2.5), NS(-1), O(0), PS(1), PM(2.5), PB(5) } of quantization factors.

(3) Steering control u

The output variable (the steering control u) controls the rotation direction and degree of the robot. The variable was based on the descriptive language and was divided into seven levels {LB, LM, LS, O, RS, RM, RB}. LB, LM and LS represent left turns for 1.8 s, 1.3 s and 0.8 s, respectively. O signifies maintenance of the current running state with no steering. RS, RM and RB represent right turns for 1.8 s, 1.3 s, and 0.8 s, respectively. The quantization levels were {-3, -2, -1, 0, 1, 2, 3}.

Selections of the type of membership function and parameters above are given in table 1, and the schematic diagram of membership function I is shown in figure 7.

Table 1: Variable types and parameters of membership functions

Variable	**Value**	**Subjection function**	
		Type	**Parameter**
Angle/Distance	NB	gauss2mf	[0.25 -4 0.25 -2.8]/ [0.5 -6 0.5 -4.6]
	NM	trapmf	[-3.4 -2.1 -1.9 -0.7]/ [-5.4 -3.15 -2.85 -1.2]
	NS	trapmf	[-2.4 -1.1 -0.9 0.4]/ [-3.2 -1.65 -1.35 -0]
	0	trapmf	[-1.4 -0.1 0.1 1.4]/ [-1.2 0 1.2]
	PS	trapmf	[-0.4 0.9 1.1 2.4]/ [0 1.35 1.65 3.2]
	PM	trapmf	[0.7 1.9 2.1 3.4]/ [1.2 2.85 3.15 5.4]
	PB	gauss2mf	[0.25 2.8 0.25 4]/ [0.5 4.6 0.5 7]
Turn control	LB	gauss2mf	[0.5 -6 0.5 -4.6]
	LM	trapmf	[-5.4 -3.15 -2.85 -1.2]
	LS	trapmf	[-3.2 -1.65 -1.35 0]
	0	trapmf	[-1.2 0 1.2]
	RS	trapmf	[0 1.35 1.65 3.2]
	RM	trapmf	[1.2 2.85 3.15 5.4]
	RB	gauss2mf	[0.5 4.574 0.5 6.974]

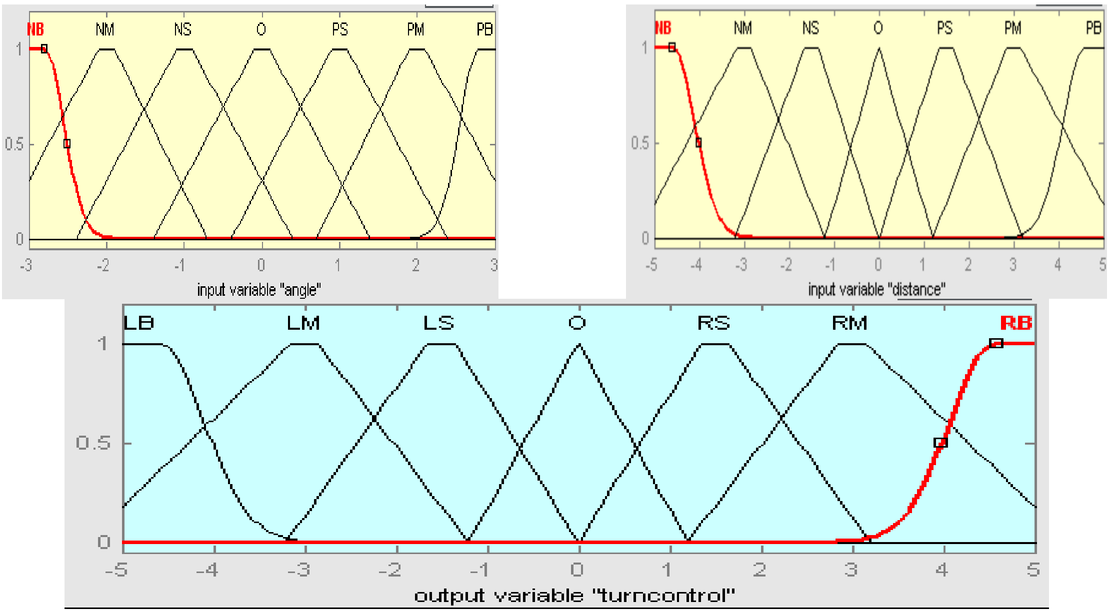


Figure 7. The schematic diagrams of membership functions

b.iii Establishment of fuzzy control rules

Fuzzy control rules are established with respect to a manual control strategy. The manual control of decision-making and technical operating experience are summarized as control algorithms based on numerical computation. Our process using language to summarize relevant knowledge is the process of establishing control rules [17]. In a fuzzy control system, the mapping from input to output is conditional on the collected definitions: the form of rules can be written as {If the condition, then the conclusion} in which conditions and inputs are related while conclusions and outputs are related. This article used a dual-input/single-output model. To combine the two inputs, a conditional statement should be summarized. Fuzzy relations can use logical "or", "and" and "not" to combine the two. In this study, the corresponding fuzzy control rules that we established were based on operating experience in the actual operation of agricultural machinery. The results are shown in table 2.

Table 2: Fuzzy control rules

Lateral deviation distance	**Heading declination angle**						
	NB	NM	NS	O	PS	PM	PB
NB	LB	LB	LM	LB	RM	RB	RB
NM	LB	LM	LS	LM	RS	RM	RB

NS	LB	LM	LS	LS	RS	RM	RB
O	LB	LS	LS	0	RS	RM	RB
PS	LB	LM	LS	RS	RS	RS	RB
PM	LM	LS	LS	RM	RS	RS	RM
PB	LS	LS	LS	RB	RS	RS	RS

In the Rule Editor Window in MATLAB, we entered the 49 rules from the above table to design the fuzzy controller. As shown in figure 8 in a more verbose mode, regular expressions appear in the following form: 1. If (Angle is NB) and (Distance is NB) then (turn control is LB) (1). The trailing "1" in brackets assigns that weight of each rule, and fuzzy rules are determined using logical “and”.

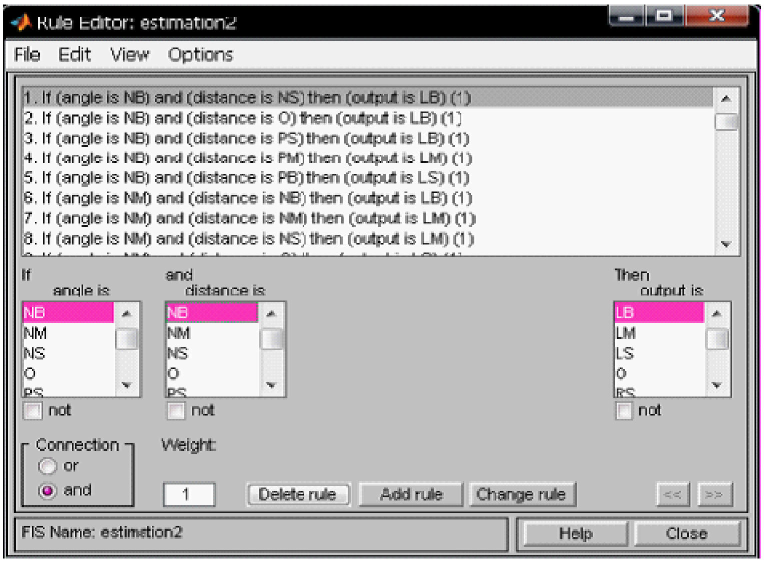


Figure 8. The fuzzy rule editing interface

b.iv Fuzzy reasoning and the defuzzification of output variables

A determination of the output variable of a fuzzy subset should make a corresponding fuzzy inference to the established fuzzy control rules. The output is just a fuzzy variable, so it cannot be used to control the object at this stage. We need to take a rational approach to convert the fuzzy variable into a precise variable so that the object can be controlled. This process is called variable defuzzification. The most common methods of variable defuzzification are MIN - MAX - gravity method, algebraic product - addition - center of gravity method, function-type inference method, weighted fuzzy reasoning, reasoning method of weighting functions, choosing the maximum degree allowed by the laws and taking the median [17].

When choosing a method, calculations that extract maximum use of the fuzzy subset tend to become very cumbersome, while some part of the information will be lost if the calculation process is simplified. We need to select an appropriate defuzzification method for the specific circumstances of the actual application under consideration. The center-of-gravity method is simple and easily meets the needs of a general anti-fuzzy system process; therefore, it gets used in a wide range of applications. We have also adopted this method. Specifically, we adopted fuzzy decision making using Mamdani's (min-max) decision-making method and defuzzification using the center-of-gravity method. The relationship between the input and output design surfaces of the fuzzy controller is shown in figure 9. The solution process for the center-of-gravity method is shown in figure 10.

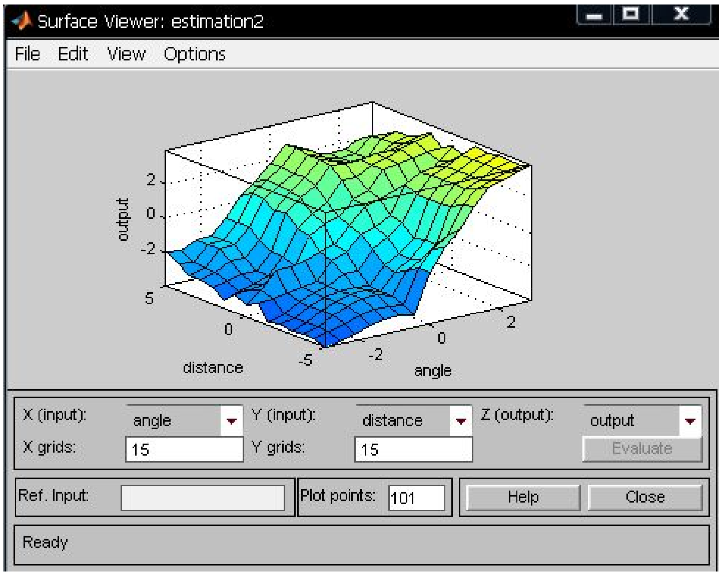


Figure 9. Output curve-surface for fuzzy control

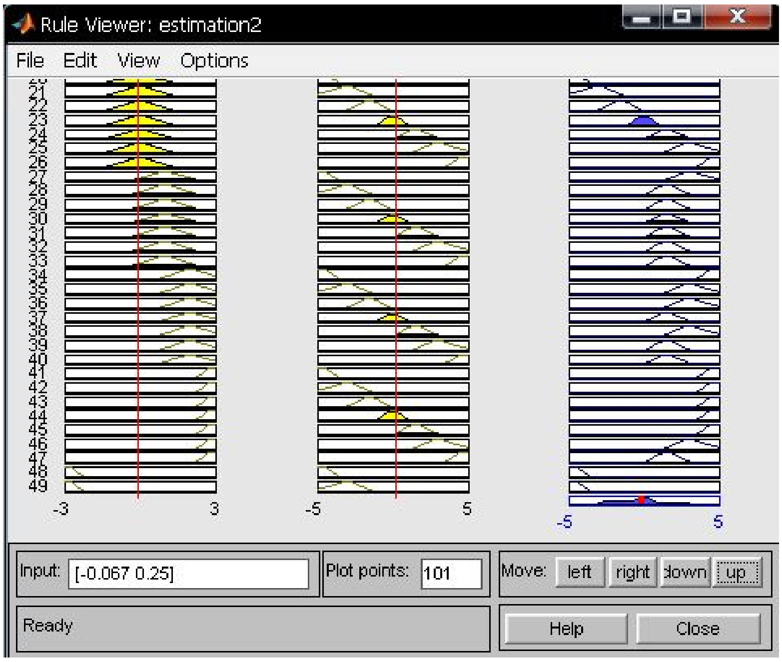


Figure 10. Anti-fuzzy gravity method

b.v Choice of the sampling time

Selection of the sampling time is a common problem in computer control, and fuzzy control, like any control process, must use a reasonable sampling time. From the actuator's point of view, the control driving signal of the output will generally require some period of time because of response delay or because the tasks need to be maintained for a certain time. Considered together with the mobility of the entire control system and anti-jamming restrictions, there should be a certain degree of continuity and reliability in the sampling time. The two navigation parameters of the system (heading angle and lateral deviation) are obtained at the same time through the visual subsystem. Therefore, the fuzzy input stimulus of the control system is determined by the frequency parameters obtained by the vision subsystem and need not be set separately. In summary, the choice of the sampling time will affect the performance of the visual subsystem and the fuzzy control system. Trial and error are needed to determine the best sampling time.

V. MODELING AND SIMULATION OF FUZZY CONTROL SYSTEM

a. Modeling of fuzzy control system

To test the fuzzy control algorithm and the control effects of the designed fuzzy controller, we used the SIMULINK package of MATLAB to perform system modeling, simulation and analysis. This package contains many sub-model libraries and functional modules, can directly create a simulation for the system model and can dynamically display the results of the simulation on an analog oscilloscope [18].

We made use of the fuzzy logic toolbox in SIMULINK to create a model of the fuzzy control system in this article as shown in figure 11. The specific creation process was to regard the two visual subsystem navigation parameters (angle and distance) as input variables of the fuzzy control system. The horizontal distance was measured in centimeters. First, it was determined whether the initial steering conditions ($|angle| \geq 2$ and $|distance| \geq 3$) were met. If they did not meet the conditions, the two control solenoid valves would not engage. If they met the conditions, corresponding changes of the two variable input units would be made to the fuzzy controller. Then, the driving strategy was determined, the judged result was output and solenoid valve condition was selected according to the range of the output variable (*turn control* > 0, right-turn; *turn control* < 0, left-turn). Finally, the delay time of the solenoid valve was chosen according to the specific values, and the valve was opened for either 0.7 s, 1 s or 1.5 s.

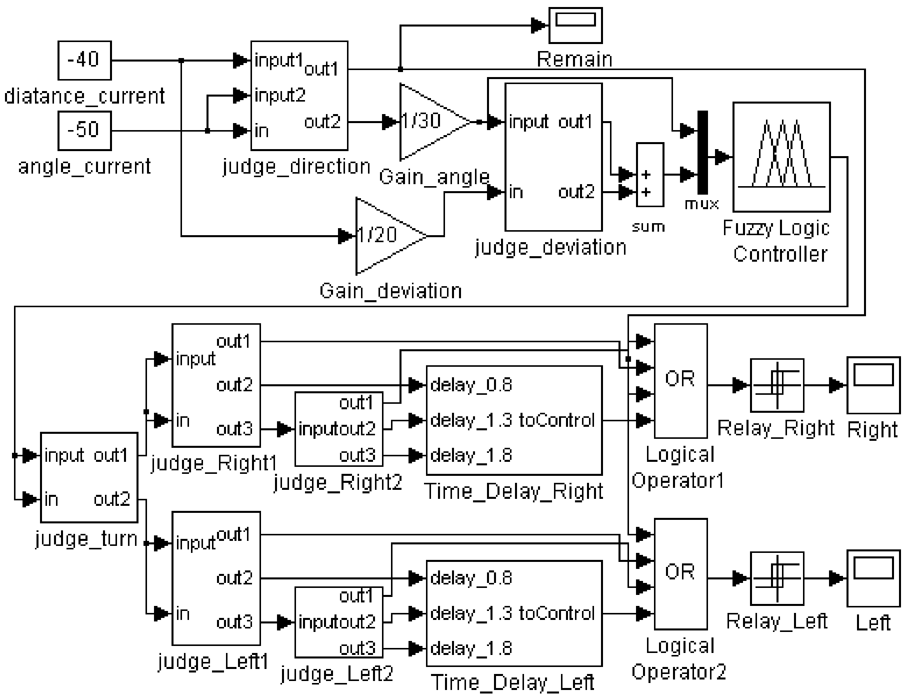
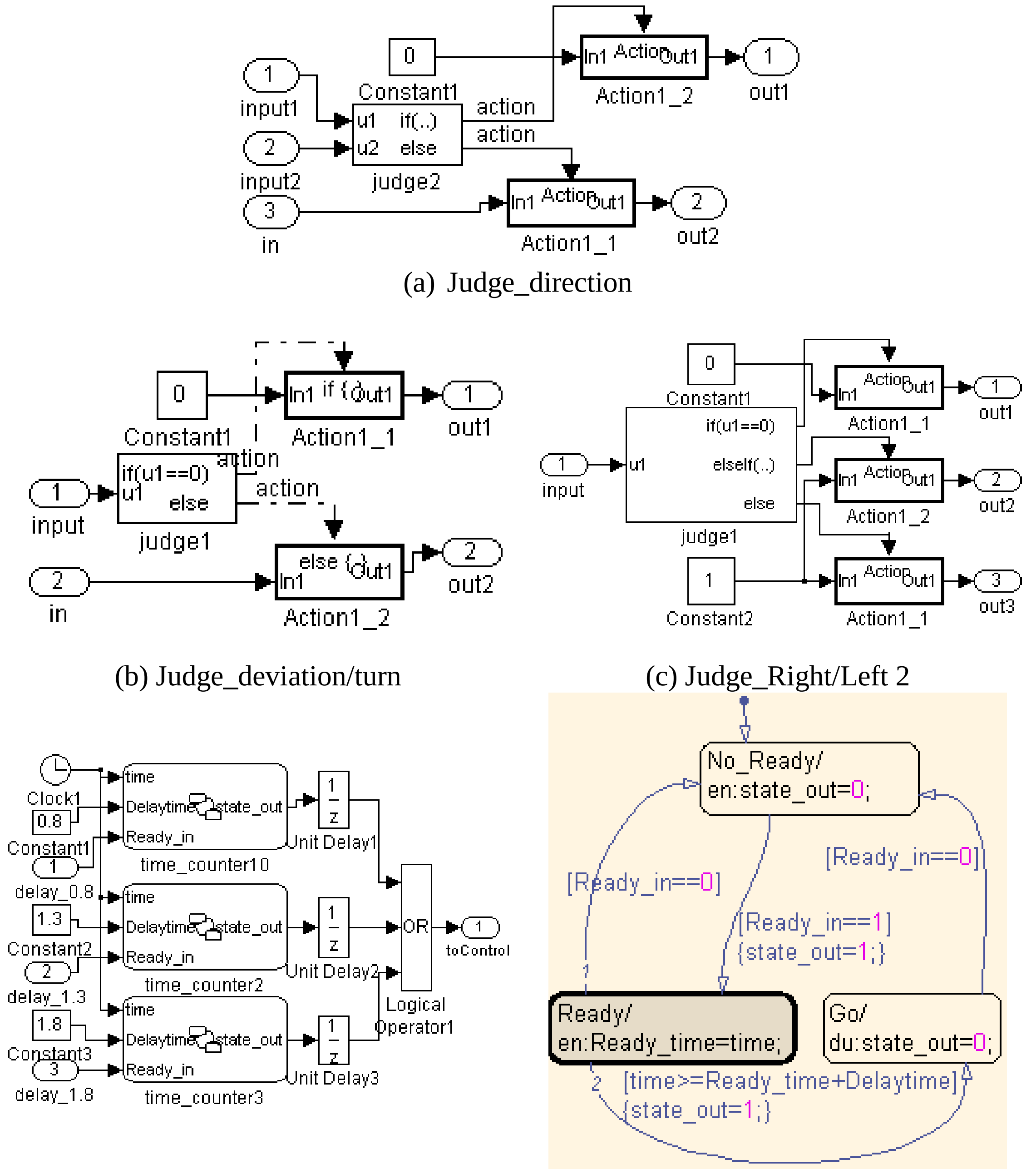


Figure 11. The model of fuzzy control system

The sub-modules (judge_direction/deviation/turn and judge_Right/Left) and the delay model (time_delay_) with its core sub-module (time_counter) are shown in figure 12.



(a) Judge_direction

(b) Judge_deviation/turn

(c) Judge_Right/Left 2

(d) Time_delay_Right/Left

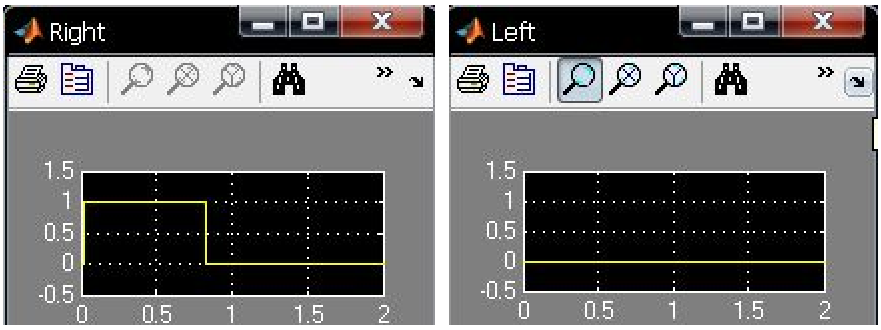
(e) Time_counter

Figure 12. The sub-module models

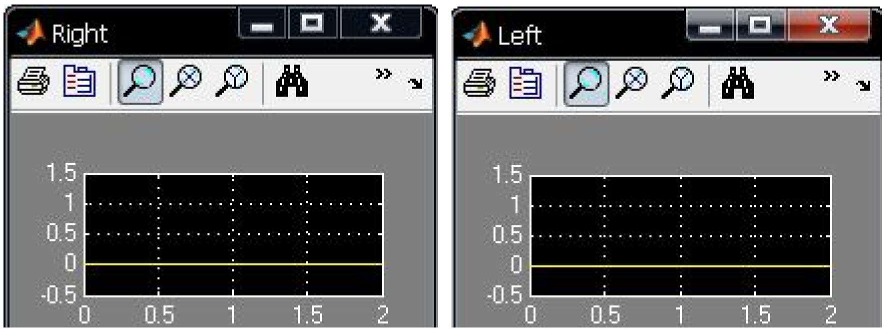
b. Fuzzy control system simulation test

The inputs of the control system are the outputs of the visual subsystem, and they are discrete input parameters with a certain time interval. Simulations were performed by entering several possible scenario parameters to test whether the designed fuzzy controller and fuzzy control system would accomplish the task accurately. The simulation results are shown in figure 13. Figure 13(a) shows a situation where the agriculture robot’s center is biased towards the left side of the straight navigation center line between the orchard lines at a distance of 10 cm.

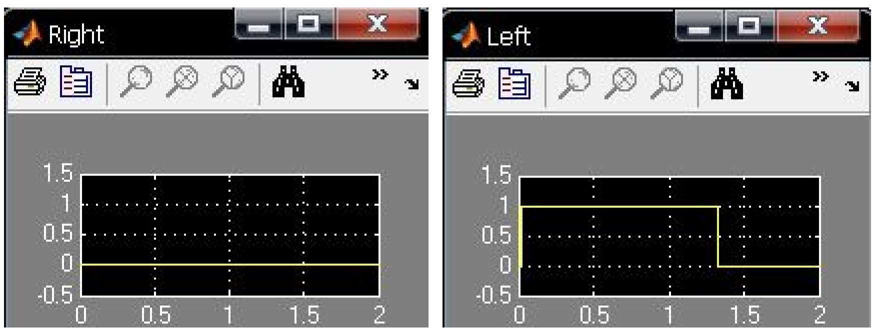
The right side of the traveling direction is biased towards the navigation path at a declination of 12°, so the agricultural robot should turn right to travel for 0.8 s, that is, make a right small turn. Figure 13 (b) also shows an agricultural robot with a center bias to the left side of the straight navigation center line at a distance of 40 cm. However, the travel direction of the bias is on the left side of the navigation path at a declination of 12°. In this case, the agricultural robot should turn left and travel for 1.3 s, that is, make a left middle turn. Figure 13 (c) indicates that when the offset distance and the angle between the agricultural robot and the navigation centerline are within a certain range, the agricultural robot travels along the original route. The scope of the defined parameters in this article is a heading declination $|\psi_w| \geq 2$ and a lateral deviation $|\rho| \geq 3$.



(a) ρ=-10 cm, ψ_w =12°



(b) ρ=-2 cm, ψ_w =2°



(c) ρ=-40 cm, ψ_w =-50°

Figure 13. The emulation of a fuzzy control system

Figure 13 shows the results of simulations using a set of parameters for each of the three described cases. The simulation results were consistent with actual agricultural robot driving conditions. A large number of experiments showed that the designed fuzzy control system can finish tasks accurately with a fast response time to meet the needs of an agricultural robot control system.

VI. CONCLUSIONS

(1) This paper analyzed and researched motion control strategies and methods of design for an agricultural robot that acquires navigational information from a visual system and uses a fuzzy control method to process and analyze information. The control system can make the appropriate decision and drive the corresponding executive body to move.
(2) As an application of the basic theory of the control method, we carried out a detailed study and design of a fuzzy control module including variable definitions, control rules, fuzzy determinations and control of the output variable.
(3) The test results of a fuzzy control system model and simulation in the SIMULINK environment of MATLAB have shown that the designed fuzzy controller provides robustness, high accuracy of reaction and good control effect.

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