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A high speed railway control system based on the fuzzy control method

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ABSTRACT

This paper proposed a high-speed railway control system based on the fuzzy control method. The fuzzy control system of the high-speed railway is designed in the Matlab software according to the expert experience and knowledge. At first the input and output variables have been fuzzified in the fuzzification process. Then the membership function is designed and the control rules are discussed in detail bring into correspondence with expert knowledge. The parameters discussion about the maximum speed and traction effort are studied in detail. Finally, the defuzzify process can output the results directly to control the high speed railway train. The results indicated that the fuzzy control system is effective and accurate in the high speed railway control process.

1. Introduction

High-speed railway development in the world especially in China has been travelling on a fast lane in recent years (Antolín et al., 2013; Feng, 2011; Zhou et al., 2013). The train speed has increased faster and faster, even to 486 km/h in late 2010. With the maximum speed raised, higher traction effort and the control method are emergency required. With the generalization of high-speed railway lines in the last decade, the interest in this theme has grown. Research has shown that along with the high speed, excessive vibrations will occur and lead to several problems (Rocha, Henriques, & Calçada, 2012; Sun, Duan, Xiong, & Zhang, 2012), such as uncomfortable of the passengers, derailment, etc.

Nowadays, the control methods of the high speed railway in the world can be divided into two kinds: one is the control manner mainly depend on the equipment and human operation for the assistant, such as the high speed railway in Japan; the other is mainly depend on human operation, represented by railways in France. The control method in China is mainly depending on the human operation. The operator should consider several parameters in every aspects, and choose suitable accelerate or brake manner. The experience of the operator has important influence on the train running states. In the real operation, some changeable factors, such as how many passengers, the running line states or the random situation, can determine the train driving performance and brake performance. Therefore, the traditional control methods cannot fit the high speed running need. It is necessary to develop some new and effective control methods which can fit the real demands.

The fuzzy control method has obvious advantageous in the uncertain system control, and can be introduced in the high speed railway control system. A fuzzy control essentially embeds the intuition and experience of a human operator, and sometimes those of an expert, designer or researcher (Aissaoui et al., 2013; Brenna et al., 2011; Ren, Duan, Li, & Philip Chen, 2013; Shen & Ye, 2013; Zhou, Zolotas, & Goodall, 2011). The fuzzy variables have values which are defined by linguistic variables such as low, high, medium, faster, slow. Each of the variables is defined by a gradually varying membership function (Chen, 2013; Eltamaly & Farh, 2013; Hsiao, 2013; Hsu, Lin, & Yeh, 2013; Lam & Lauber, 2013; Onieva, Godoy, Villagrá, Milanés, & Pérez, 2013). The fuzzy rules are essentially the control strategy of the expert control system. It is usually obtained from expert experiences, knowledge or heuristics; it contains a collection of fuzzy conditional statements expressed as a set of IF–THEN rules (Boulkroune, Tadjineb, Saad, & Farza, 2010; Das, Pan, & Das, 2013; Pan, Zhou, Sun, Sun, & Er, 2013; Tong & Qian, 2013).

Based on the above observations, this paper further considers the problem of high speed railway control methods, and then discusses the parameters which effluence the railway operation and introduced the fuzzy control method into the high speed railway control.

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This paper is discussed in the next nine sections. Section 2 introduces the simple fuzzy control system method. The control objects in the high speed railway fuzzy control system in this paper is discussed in Section 3. Section 4 deals with the fuzzification process in the control system. The membership function, the fuzzy control rules and the fuzzy relationship are discussed in the Sections 5, 6, and 7, respectively. The fuzzy inference and defuzzify process of the system is discussed in Section 8. The whole system analysis and simulation is discussed in detail in Section 9 and finally some conclusions are summarized in Section 10.

2. Basic fuzzy control system combination

A basic fuzzy control system is combined of the following five steps: variable definition, fuzzification, knowledge base, logic judgment and defuzzify (Mabrouk, Cheriet, & Feliachi, 2013; Wang et al., 2013).

2.1. Variable definition

All the variables should be defined before the system analysis. For example, in the basic control problems, the error E between the input variable and the output variable, the rate of output error change EC, both the E and EC can be named by a joint name, which is fuzzy variable in the fuzzy system.

2.2. Fuzzification

The fuzzification is the process that to change the input variables into some suitable values in the domain of discourse, and to describe the measured physical quantities using colloquial variables. We can calculate the corresponding membership values according to the suitable linguistic values. These colloquial variables can be named fuzzy subsets.

2.3. Knowledge base

The knowledge base includes data base and the rule base. The data base can supply the definition of the functions to deal with the fuzzy data. The rule base can describe the control objects and strategies based on the theoretical control rules.

2.4. Logic judgment

This part is the most important in the fuzzy system controller. It can modify the human thinking and deduce the fuzzy control signals using fuzzy logic and fuzzy syllogism like human.

2.5. Defuzzify

This process is opposite to the fuzzification process. It can transform the fuzzy values into the specific control signals as the output of the system.

3. The control objects of the high speed railway fuzzy control system

3.1. Input variables

The objects of the high speed railway fuzzy control system when the high speed railway train is running, such as operate steadily, saving the energy, riding comfortable, high speed, operate safely, etc. Therefore the control system should optimize the operation process according to these parameters. For example, when the high speed railway train needs to be stopped, the late speed cut and heavy brake operation can raise the running speed, but brings running unsteady and wasting energy. It is important to choose some best variables according many indexes and do the evaluation of the control system.

In our designed system the input variables are mainly six as shown below.

(1) Parking accuracy

The accuracy in the parking process can be abbreviated as A, which is defined as the relative distance between the object parking position and the calculated parking position.

(2) Riding comfort level

The Comfort level of Riding is abbreviated as C. It is difficult to directly measure the comfort level. However, the research results show that it is insensitive for the human being to the around direction vibration, but sensitive to the vertical direction. Therefore, the sensors which are used to collect the vertical direction vibration can give some parameters to reflect the comfort level of riding.

(3) Energy saving

Abbreviated as E. In this control system E is judged by the electric quantity every 100 km when the high speed railway train is running.

(4) Running time

Abbreviated as R. It is defined as the time between the rail leaving from the last station and arriving to the next station.

(5) Safety

Abbreviated as S. The safety can judge the safe condition when the high speed railway train is running, such as out rail coefficient, possibility of the turnover, etc. When the high speed railway train runs in the straight rail, the safety is higher. The safety will be much lower when the rail in running into a hole, meeting the other rail, or making a turn with high speed.

(6) Traceability of speed

Abbreviated as T. It is defined as the consistency of the running speed and the calculated speed of the high speed railway train.

3.2. Output variables

The output variables of the control system include the following two factors.

(1) Controlling value of the speed

Abbreviated as N. It is defined as the speed domain of the current high speed railway train should be controlled in.

(2) Variable quantity relative to N

Abbreviated as NC. It indicates the present action commands to the high speed railway train, and directly controls the rail speed.

4. Fuzzification of the variables in the control system

The smaller of the distance between object parking position and the calculated parking position, the higher the value of A. The fuzzy subsets of A are $\widetilde{A}_1, \widetilde{A}_2, \widetilde{A}_3, \widetilde{A}_4, \widetilde{A}_5$, its linguistic subsets and linguistic variables are as follows

$$A = \{\text{very bad}, \text{bad}, \text{medium}, \text{good}, \text{very good}\} = \{VB, B, M, G, VG\} \quad (1)$$

The value of A is quantified into five grades, represented as $\{-2, -1, 0, +1, +2\}$ respectively. Its discourse domain is

$$U_a\{-2, -1, 0, +1, +2\} \quad (2)$$

The reasonable range of the distance between object parking position and the calculated parking position is 0–50 cm, so the quantified relationship is shown in Table 1, in which the unit is cm.

The fuzzification processes of C, E, R, S, T, N and NC are similar to A. Therefore, we can use the following table to combine these parameters as shown in Table 2.

As shown in Table 2, the word "ibid" indicates that the content in the space is the same as the above space. The research shows that, when people ride the high speed railway train, he is sensitive to the vertical direction vibration. When the vibration increases, people will feel uncomfortable, even feel sick or vomit. If the passengers feel uncomfortable, it is necessary to change the running parameters of the high speed railway train. The reasonable range of the vertical direction vibration that people feel comfortable is 0–50 Hz, so the quantified relationship is shown in Table 2, in which the unit is Hz.

The quantified relationship of E is shown in Table 2, in which the unit is kilowatt hour.
The unit of quantified relationship of R is minute.
The value of S in Table 2 is the safety factor.
The unit of quantified relationship of T, N, and NC are all km/h.

Table 1
Quantified value of A.

A	Quantified value
$0 \leqslant A \leqslant 10$	+2
$10 < A \leqslant 20$	+1
$20 < A \leqslant 30$	0
$30 < A \leqslant 40$	−1
$40 < A \leqslant 50$	−2

5. Membership function

For a given fuzzy set, the membership function can reflect the fuzziness. It is an important problem to ensure the function in the fuzzy control process. According to the expert experience and the reality analysis, we can obtain the vector form of the membership functions in the input and output variables, as shown in Tables 3–5.

6. The establishment of Fuzzy control rules

The fuzzy control rules are mainly depending on the control experience and the expert knowledge, which are knowledge models but not mathematical models (Abbadi, Nezli, & Boukhetala, 2013; Taleizadeh, Akhavan Niaki, Aryanezhad, & Shafii, 2013;

Table 2
Fuzzification of the variables in the fuzzy control system.

	Fuzzy subsets	Linguistic subsets	Variables	Discourse domain	Quantified relationship	Value
C	$\widetilde{C}_i$ $i = 1, \ldots, 5$	Very bad	VB	U_C={−2, −1, 0,+1, +2}	$0 \leqslant C \leqslant 2$	+2
		Bad	B		$2 < C \leqslant 4$	+1
		Medium	M		$4 < C \leqslant 6$	+0
		Good	G		$6 < C \leqslant 8$	−1
		Very good	VG		$8 < C \leqslant 10$	−2
E	$\widetilde{E}_i$ $i = 1, \ldots, 5$	ibid	ibid	U_E={−2, −1, 0, +1, +2}	$3.60 \leqslant E \leqslant 3.64$	+2
					$3.64 < E \leqslant 3.68$	+1
					$3.68 < E \leqslant 3.72$	+0
					$3.72 < E \leqslant 3.76$	−1
					$3.76 < E \leqslant 3.80$	−2
S	$\widetilde{S}_i$ $i = 1, \ldots, 5$	ibid	ibid	U_S={−2, −1, 0, +1, +2}	$0 \leqslant S \leqslant 2$	−2
					$2 < S \leqslant 4$	−1
					$4 < S \leqslant 6$	0
					$6 < S \leqslant 8$	+1
					$8 < S \leqslant 10$	+2
T	$\widetilde{T}_i$ $i = 1, \ldots, 5$	ibid	Ibid	U_T={−2, −1, 0, +1, +2}	$0 \leqslant T \leqslant 4$	+2
					$4 < T \leqslant 8$	+1
					$8 < T \leqslant 12$	0
					$12 < T \leqslant 16$	−1
					$16 < T \leqslant 20$	−2
R	$\widetilde{R}_i$ $i = 1, \ldots, 5$	Very short	VS	U_R={−2, −1, 0, +1, +2}	$20 \leqslant R \leqslant 24$	−2
		Short	S		$24 < R \leqslant 28$	−1
		Medium	M		$28 < R \leqslant 32$	0
		Long	L		$32 < R \leqslant 36$	+1
		Very long	VL		$36 < R \leqslant 40$	+2
N	$\widetilde{N}_i$ $i = 1, \ldots, 6$	Stop	N0	U_N={0, +1, +2, +3, +4, +5}	N = 0	0
		Low	N1		$0 < N \leqslant 60$	+1
		Medium low	N2		$60 < N \leqslant 120$	+2
		Medium	N3		$120 < N \leqslant 180$	+3
		Medium high	N4		$180 < N \leqslant 240$	+4
		High	N5		$240 < N \leqslant 300$	+5
NC	$\widetilde{N}\breve{C}_i$ $i = 1, \ldots, 7$	Stop	N1	U_{NC}={+1, +2, +3, +4, +5, +6, +7}	N = −240	+1
		Brake hard	N2		$-240 < NC \leqslant 120$	+2
		Brake little	N3		$-120 < NC < 0$	+3
		Medium	N4		NC = 0	+4
		Fast	N5		$0 < NC \leqslant 120$	+5
		Faster	N6		$120 < NC \leqslant 240$	+6
		Fastest	N7		$240 < N \leqslant 300$	+7

Table 3
Vector table of the membership function in A, C, E, R, S, T.

	−2	−1.5	−1	−0.5	0	+0.5	+1	+1.5	+2
VB	1.0	0.2	0	0	0	0	0	0	0
B	0	0.2	1.0	0.2	0	0	0	0	0
M	0	0	0	0.2	1.0	0.2	0	0	0
G	0	0	0	0	0	0.2	1.0	0.2	0
VG	0	0	0	0	0	0	0	0.2	1.0

Table 4
Vector table of the membership function in N.

	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6
N0	0.1	1.0	0.1	0	0	0	0	0	0	0	0	0	0
N1	0	0	0.1	1.0	0.1	0	0	0	0	0	0	0	0
N2	0	0	0	0	0.1	1.0	0.1	0	0	0	0	0	0
N3	0	0	0	0	0	0	0.1	1.0	0.1	0	0	0	0
N4	0	0	0	0	0	0	0	0	0.1	1.0	0.1	0	0
N5	0	0	0	0	0	0	0	0	0	0	0.1	1.0	0.1

Chang & Yang, 2011; Shi & Shen, 2013). The accuracy of these models can reflect whether the fuzzy process summarized the successful experiences and the expert knowledge, they can also determine the control performance. In some means, the fuzzy control rules are expert system knowledge in expert control systems. The principle of designing the fuzzy control rules is that, when the error becomes bigger, the control quantity of the system should have the ability to reduce the error directly and effectively. When the error is smaller, we not only need to eliminate the error, but also to consider the error changes to guarantee the stability of the system.

Therefore, according to the demand of the high speed railway, some rules can be summarized as follows.

6.1. Constant speed running between two stations

Rule 1: In order to guarantee the safety and riding comfortable, when the speed is higher than the restricted speed, the system should adjust the output variables into the suitable value, which is between current control value and the emergency brake control value.
Rule 2: In order to save the energy, we can use inertia force to run the rail based on the running time can be guaranteed. This time, neither acceleration nor brake.
Rule 3: In order to shorten the running time, when the speed is smaller than the restrict speed, we can choose the highest acceleration.
Rule 4: In order to guarantee the riding comfortable, if the current control value can maintain the running speed, this need not to be changed.
Rule 5: It is necessary to adjust the control value, to make the value around the suitable control value.

6.2. Station parking control rules

According to the expert experiences on the high speed railway control operation, when the rail has passed the parking sign before the station, the control value can be changed immediately, at the same time, the riding comfortable should be considered.

Rule 1: For the riding comfortable, when passing the parking sign, the brake operation cannot be used to avoid inertia shock.
Rule 2: In order to shorten the running time, after the sign, the slowly brake is needed.
Rule 3: In order to parking accurately, the control value should be changed several times, to avoid inertia shock and at the same time parking at the given position.

Some detail control rules of the fuzzy control system are as follows.

$\widetilde{R}_1$: If S = VB or C = VB then N = N0 and NC = NC1;
$\widetilde{R}_2$: If S = B or C = B then N = N1 and NC = NC1;
$\widetilde{R}_3$: If S = M and C = M and T = VS then N = N1 and NC = NC2;
$\widetilde{R}_4$: If S = M and C = G and T = VS then N = N2 and NC = NC2;
$\widetilde{R}_5$: If S = M and C = VG and T = VS then N = N3 and NC = NC3;
$\widetilde{R}_6$: If S = M and C = M and T = S then N = N1 and NC = NC2;
$\widetilde{R}_7$: If S = M and C = G and T = S then N = N2 and NC = NC3;
$\widetilde{R}_8$: If S = M and C = VG and T = S then N = N3 and NC = NC3;
$\widetilde{R}_9$: If S = M and C = M and T = M then N = N1 and NC = NC3;
$\widetilde{R}_{10}$: If S = M and C = G and T = M then N = N2 and NC = NC3;
$\widetilde{R}_{11}$: If S = M and C = VG and T = M then N = N3 and NC = NC4;
$\widetilde{R}_{12}$: If S = M and C = M and T = L then N = N1 and NC = NC3;
$\widetilde{R}_{13}$: If S = M and C = G and T = L then N = N2 and NC = NC4;
$\widetilde{R}_{14}$: If S = M and C = VG and T = L then N = N3 and NC = NC5;
$\widetilde{R}_{15}$: If S = M and C = M and T = VL then N = N1 and NC = NC4;
$\widetilde{R}_{16}$: If S = M and C = G and T = VL then N = N2 and NC = NC5;
$\widetilde{R}_{17}$: If S = M and C = VG and T = VL then N = N3 and NC = NC5;
$\widetilde{R}_{18}$: If S = G and C = M and T = VS then N = N2 and NC = NC2;
$\widetilde{R}_{19}$: If S = G and C = G and T = VS then N = N3 and NC = NC3;
$\widetilde{R}_{20}$: If S = G and C = VG and T = VS then N = N4 and NC = NC3;
$\widetilde{R}_{21}$: If S = G and C = M and T = S then N = N2 and NC = NC3;
$\widetilde{R}_{22}$: If S = G and C = G and T = S then N = N3 and NC = NC3;
$\widetilde{R}_{23}$: If S = G and C = VG and T = S then N = N4 and NC = NC4;
$\widetilde{R}_{24}$: If S = G and C = M and T = M then N = N2 and NC = NC3;
$\widetilde{R}_{25}$: If S = G and C = G and T = M then N = N3 and NC = NC4;
$\widetilde{R}_{26}$: If S = G and C = VG and T = M then N = N4 and NC = NC5;
$\widetilde{R}_{27}$: If S = G and C = M and T = L then N = N2 and NC = NC4;
$\widetilde{R}_{28}$: If S = G and C = G and T = L then N = N3 and NC = NC5;
$\widetilde{R}_{29}$: If S = G and C = VG and T = L then N = N4 and NC = NC5;
$\widetilde{R}_{30}$: If S = G and C = M and T = VL then N = N2 and NC = NC5;
$\widetilde{R}_{31}$: If S = G and C = G and T = VL then N = N3 and NC = NC5;
$\widetilde{R}_{32}$: If S = G and C = VG and T = VL then N = N4 and NC = NC6;
$\widetilde{R}_{33}$: If S = VG and C = M and T = VS then N = N3 and NC = NC3;
$\widetilde{R}_{34}$: If S = VG and C = G and T = VS then N = N4 and NC = NC3;
$\widetilde{R}_{35}$: If S = VG and C = VG and T = VS then N = N4 and NC = NC3;
$\widetilde{R}_{36}$: If S = VG and C = M and T = S then N = N3 and NC = NC3;

Table 5
Vector table of the membership function in NC.

	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7
NC1	0.1	1.0	0.1	0	0	0	0	0	0	0	0	0	0	0	0
NC2	0	0	0.1	1.0	0.1	0	0	0	0	0	0	0	0	0	0
NC3	0	0	0	0	0.1	1.0	0.1	0	0	0	0	0	0	0	0
NC4	0	0	0	0	0	0	0.1	1.0	0.1	0	0	0	0	0	0
NC5	0	0	0	0	0	0	0	0	0.1	1.0	0.1	0	0	0	0
NC6	0	0	0	0	0	0	0	0	0	0	0.1	1.0	0.1	0	0
NC7	0	0	0	0	0	0	0	0	0	0	0	0	0.1	1.0	0.1

Table 6
Parameters in fuzzification.

	Discourse domain	Fuzzy subsets	Membership function	Details
C	[−2,2]	VB	Trigonometric function	[−2 −2 −1.4]
		B		[−1.6 −1 −0.4]
		M		[−0.6 0 0.6]
		G		[0.4 1 1.6]
		VG		[1.4 2 2]
E	ibid	ibid	ibid	ibid
S	ibid	ibid	ibid	ibid
T	ibid	ibid	ibid	ibid
R	ibid	VS	ibid	ibid
		S		
		M		
		L		
		VL		
N	[0,6]	N0	ibid	[0 0.5 1]
		N1		[1 1.5 2]
		N2		[2 2.5 3]
		N3		[3 3.5 4]
		N4		[4 4.5 5]
		N5		[5 5.5 6]
NC	[0,7]	NC1	ibid	[0 0.5 1]
		NC2		[1 1.5 2]
		NC3		[2 2.5 3]
		NC4		[3 3.5 4]
		NC5		[4 4.5 5]
		NC6		[5 5.5 6]
		NC7		[6 6.5 7]

$\widetilde{R}_{37}$: If S = VG and C = G and T = S then N = N3 and NC = NC3;
$\widetilde{R}_{38}$: If S = VG and C = VG and T = S then N = N4 and NC = NC3;
$\widetilde{R}_{39}$: If S = VG and C = M and T = M then N = N3 and NC = NC4;
$\widetilde{R}_{40}$: If S = VG and C = G and T = M then N = N4 and NC = NC5;
$\widetilde{R}_{41}$: If S = VG and C = VG and T = M then N = N4 and NC = NC5;
$\widetilde{R}_{42}$: If S = VG and C = M and T = L then N = N3 and NC = NC5;
$\widetilde{R}_{43}$: If S = VG and C = G and T = L then N = N4 and NC = NC5;
$\widetilde{R}_{44}$: If S = VG and C = M and T = VL then N = N3 and NC = NC5;
$\widetilde{R}_{45}$: if S = VG and C = G and T = VL then N = N4 and NC = NC6;
$\widetilde{R}_{46}$: If S = VG and C = VG and T = L and A is VB or E is VB or T is VB then N = N3 and NC = NC5;
$\widetilde{R}_{47}$: If S = VG and C = VG and T = L and A is B or E is B or T is B then N = N4 and NC = NC5;
$\widetilde{R}_{48}$: If S = VG and C = VG and T = L and A is M or E is M or T is M then N = N4 and NC = NC5;
$\widetilde{R}_{49}$: If S = VG and C = VG and T = L and A is G or VG and E is G or VG and T is G or VG then N = N5 and NC = NC6;
$\widetilde{R}_{50}$: If S = VG and C = VG and T = VL and A is VB or E is VB or T is VB then N = N3 and NC = NC5;
$\widetilde{R}_{51}$: If S = VG and C = VG and T = VL and A is B or E is B or T is B then N = N4 and NC = NC6;
$\widetilde{R}_{52}$: If S = VG and C = VG and T = VL and A is M or E is M or T is M then N = N4 and NC = NC6;
$\widetilde{R}_{53}$: If S = VG and C = VG and T = VL and A is G or VG and E is G or VG and T is G or VG then N = N5 and NC = NC7。.

7. Fuzzy relationship

The fuzzy relationship is calculated by the Mamdani minimum operation method (Dong, Wang, & Yang, 2011; Wang, Chen, & Lin, 2013; Wanga, Wang, & Chai, 2013). For example, when we want to calculate the fuzzy relationship of control rule $\widetilde{R}_6$

$$\widetilde{R}_6 : \text{if } S = M \quad \text{and} \quad C = M \quad \text{and} \quad T = S \quad \text{then} \quad N = N1 \quad \text{and} \quad NC = NC2;$$

By forming the definition of the fuzzy subsets we can obtain

$$\widetilde{R}_{6-1} = (\widetilde{S}_3 \times \widetilde{N}_1) \cap (\widetilde{C}_3 \times \widetilde{N}_1) \cap (\widetilde{T}_3 \times \widetilde{N}_1) \tag{3}$$

$$\widetilde{R}_{6-2} = (\widetilde{S}_3 \times \widetilde{NC}_2) \cap (\widetilde{C}_3 \times \widetilde{NC}_2) \cap (\widetilde{T}_3 \times \widetilde{NC}_2) \tag{4}$$

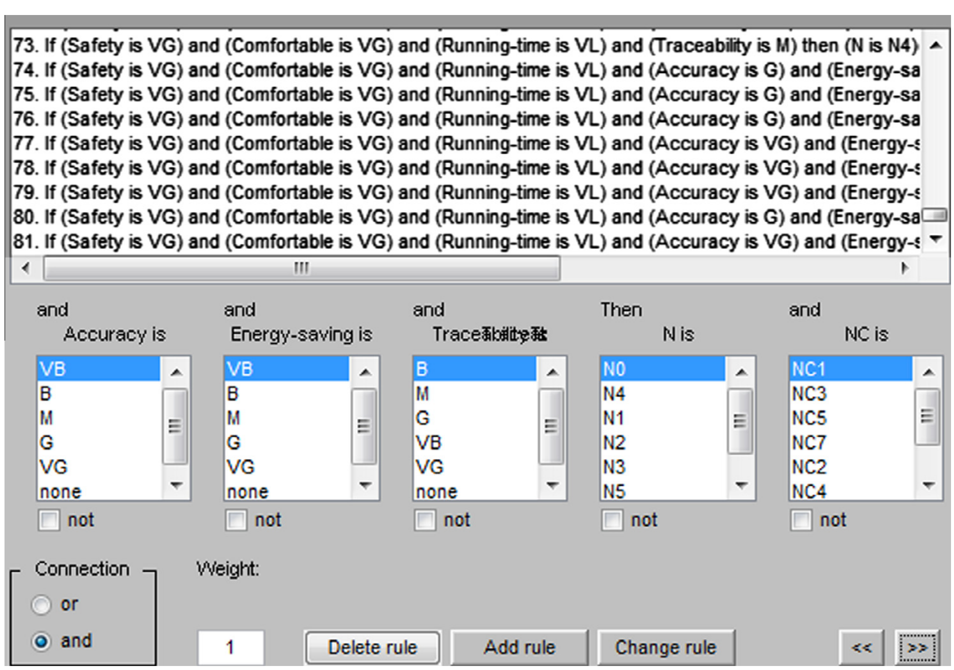

Fig. 1. The sketch map of control rules.

$$\widetilde{R}_{S1} = \widetilde{S}_3 \times \widetilde{N}_1 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0.2 \\ 1.0 \\ 0.2 \\ 0 \\ 0 \\ 0 \end{bmatrix} \times [0 \;\; 0 \;\; 0.1 \;\; 1.0 \;\; 0.1 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0]$$

$$= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0.2 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 1.0 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0.2 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (5)$$

$$\widetilde{R}_{S2} = \widetilde{S}_3 \times \widehat{N}\underset{2}{\breve{C}} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0.2 \\ 1.0 \\ 0.2 \\ 0 \\ 0 \\ 0 \end{bmatrix} \times [0 \;\; 0 \;\; 0.1 \;\; 1.0 \;\; 0.1 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0]$$

$$= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0.2 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 1.0 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0.2 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (6)$$

$$\widetilde{R}_{C1} = \widetilde{C}_3 \times \widetilde{N}_1 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0.2 \\ 1.0 \\ 0.2 \\ 0 \\ 0 \\ 0 \end{bmatrix} \times [0 \;\; 0 \;\; 0.1 \;\; 1.0 \;\; 0.1 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0]$$

$$= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0.2 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 1.0 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0.2 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (7)$$

$$\widetilde{R}_{C2} = \widetilde{C}_3 \times \widehat{N}\underset{2}{\breve{C}} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0.2 \\ 1.0 \\ 0.2 \\ 0 \\ 0 \\ 0 \end{bmatrix} \times [0 \;\; 0 \;\; 0.1 \;\; 1.0 \;\; 0.1 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0]$$

$$= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0.2 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 1.0 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0.2 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (8)$$

$$\widetilde{R}_{T1} = \widetilde{T}_3 \times \widetilde{N}_1 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0.2 \\ 1.0 \\ 0.2 \\ 0 \\ 0 \\ 0 \end{bmatrix} \times [0 \;\; 0 \;\; 0.1 \;\; 1.0 \;\; 0.1 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0]$$

$$= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0.2 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 1.0 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0.2 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (9)$$

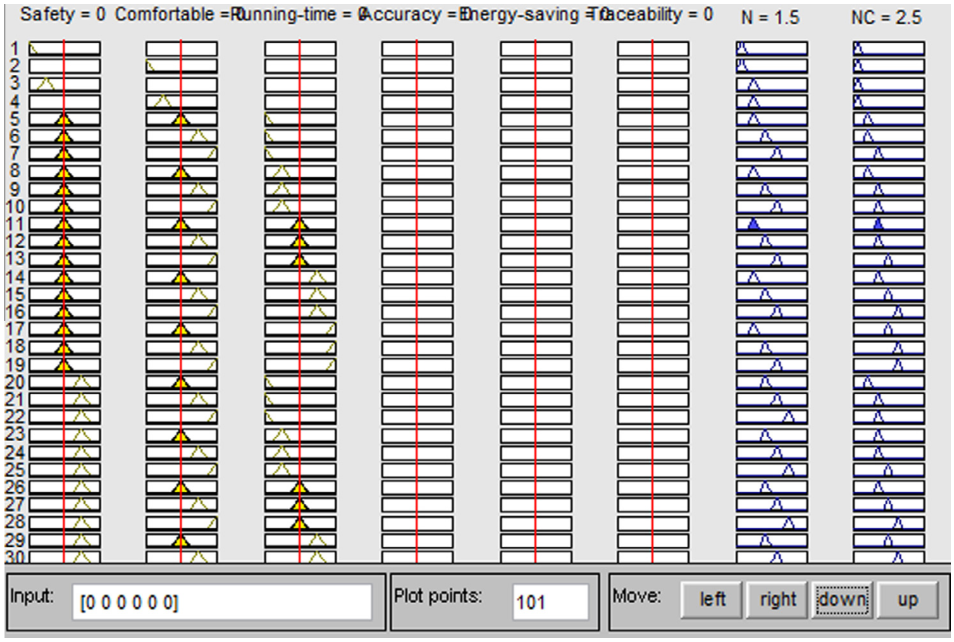

Fig. 2. Output variables in the system.

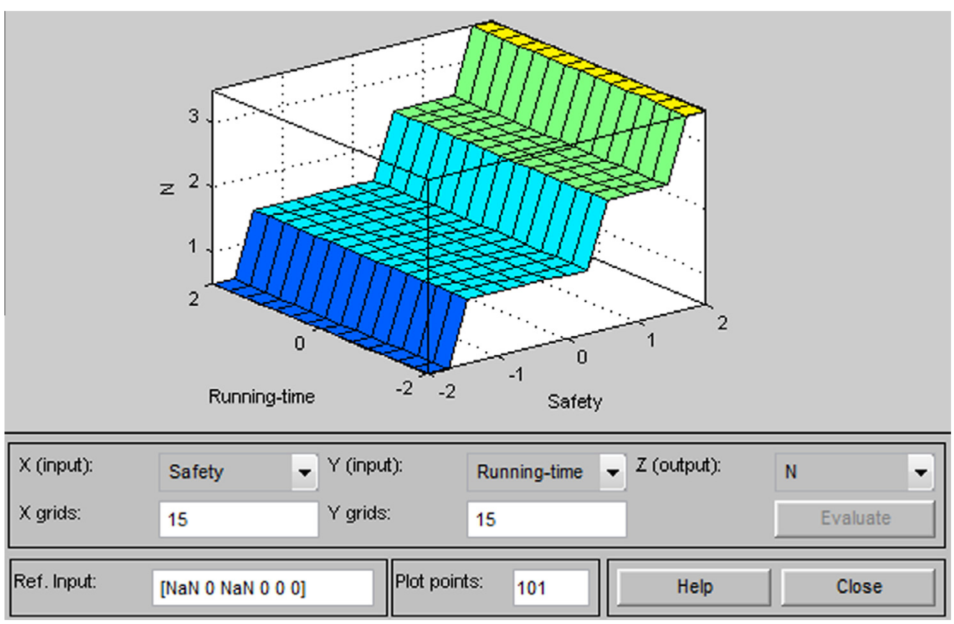

Fig. 3. The relationship between running time, safety and N.

$$\widetilde{R}_{T2} = \widetilde{T}_3 \times \widehat{N}\,\underset{2}{\breve{C}} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0.2 \\ 1.0 \\ 0.2 \\ 0 \\ 0 \\ 0 \end{bmatrix} \times [0\ \ 0\ \ 0.1\ \ 1.0\ \ 0.1\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0] = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0.2 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 1.0 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0.2 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (10)$$

$$\widetilde{R}_{6-1} = \widetilde{R}_{S1} \cap \widetilde{R}_{C1} \cap \widetilde{R}_{T1}$$

$$= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0.2 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 1.0 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0.2 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (11)$$

$$\widetilde{R}_{6-2} = \widetilde{R}_{S2} \cap \widetilde{R}_{C2} \cap \widetilde{R}_{T2}$$

$$= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0.2 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 1.0 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0.2 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (12)$$

In the same calculation method, we can obtain the whole fuzzy relationship of the control system.

8. Fuzzy inference and defuzzify

When the fuzzy relationship of the fuzzy controller a calculated, the fuzzy value vector can be deduced using the combining inference method. For any given quantized input variable a and b, the maximum membership function is corresponding to the fuzzy sets $\widetilde{A}_i$ and $\widetilde{B}_j$, the output fuzzy vector $\widetilde{U}_k$ can be deduced as

$$\widetilde{U}_k = (\widetilde{A}_i \circ \widetilde{R}_A) \cap (\widetilde{B}_j \circ \widetilde{R}_B) \quad (13)$$

Table 7
Simulation results.

NO.	Input	Output						
	S	C	R	A	E	T	N	NC
1	−2	1	2	−1	−2	1	0.5	0.5
2	0	−1	2	0	1	−2	1.5	0.5
3	0	−1	−2	0	1	−2	1.5	0.5
4	0	2	−1	−2	0	−1	3.5	2.5
5	0	0	0	0	2	0	1.5	2.5
6	0	1	0	2	2	1	2.5	2.5
7	0	0	1	1	−2	0	1.5	2.5
8	0	2	1	1	−1	2	3.5	4.5
9	0	−2	2	2	0	1	0.5	0.5
10	0	0	2	2	2	1	1.5	3.5
11	1	−1	−2	−1	0	−2	1.5	0.5
12	1	2	−2	0	1	−2	4.5	2.5
13	1	2	−1	0	−2	−1	4.5	3.5
14	1	−2	−1	0	−2	−1	0.5	0.5
15	1	0	0	2	−1	0	2.5	2.5
16	1	1	0	−1	0	−1	3.5	3.5
17	1	1	1	2	−1	2	3.5	4.5
18	1	2	1	−2	2	−2	4.5	4.5
19	1	1	2	0	1	−1	3.5	4.5
20	1	0	2	1	2	−1	2.5	4.5
21	2	0	−2	1	1	0	3.5	2.5
22	2	2	−2	2	−2	−1	4.5	3.5
23	2	1	−1	0	−1	−2	3.5	2.5
24	2	2	−1	0	2	2	4.5	3.5
25	2	0	0	−2	1	1	3.5	3.5
26	2	2	0	−1	1	2	4.5	4.5
27	2	1	1	−1	2	0	4.5	4.5
28	2	0	1	2	0	2	3.5	4.5
29	2	2	2	1	2	1	5.5	6.5
30	2	1	2	−1	2	2	4.5	5.5

where, the output result is a fuzzy vector, which cannot be used to control the objects. Therefore it is necessary to transform the fuzzy vector into an accurate specific value, which can be used in the follow control process. This process is named defuzzify.

In this fuzzy control system, we choose the method of weighted mean, which is also called centroid method.

$$u = \frac{\sum_{j=1}^{n} u_{cj(\omega j)} \omega j}{\sum_{j=1}^{n} u_{cj(\omega j)}} \quad (14)$$

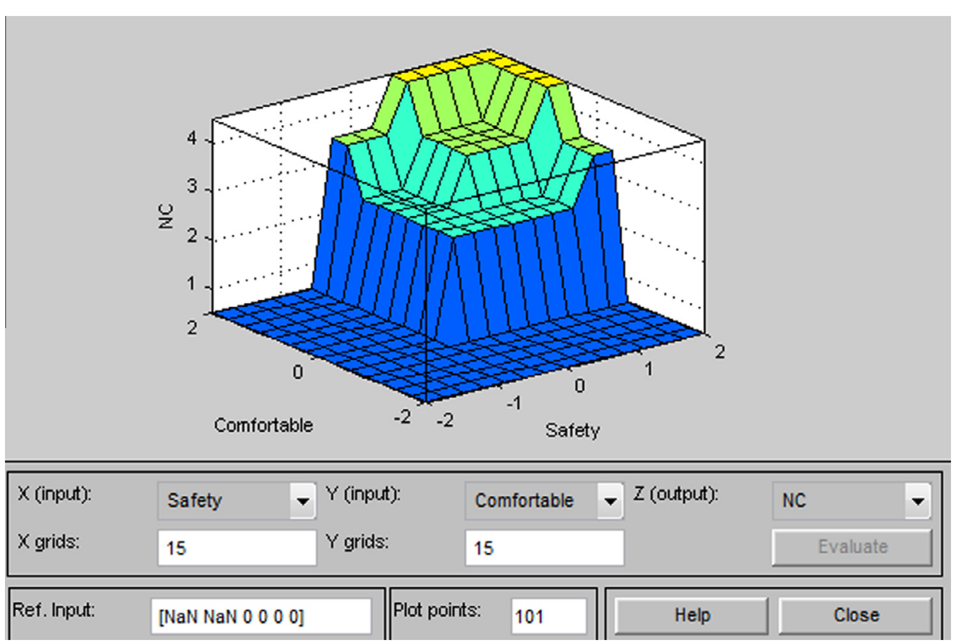

Fig. 4. The relationship between comfortable, safety and NC.

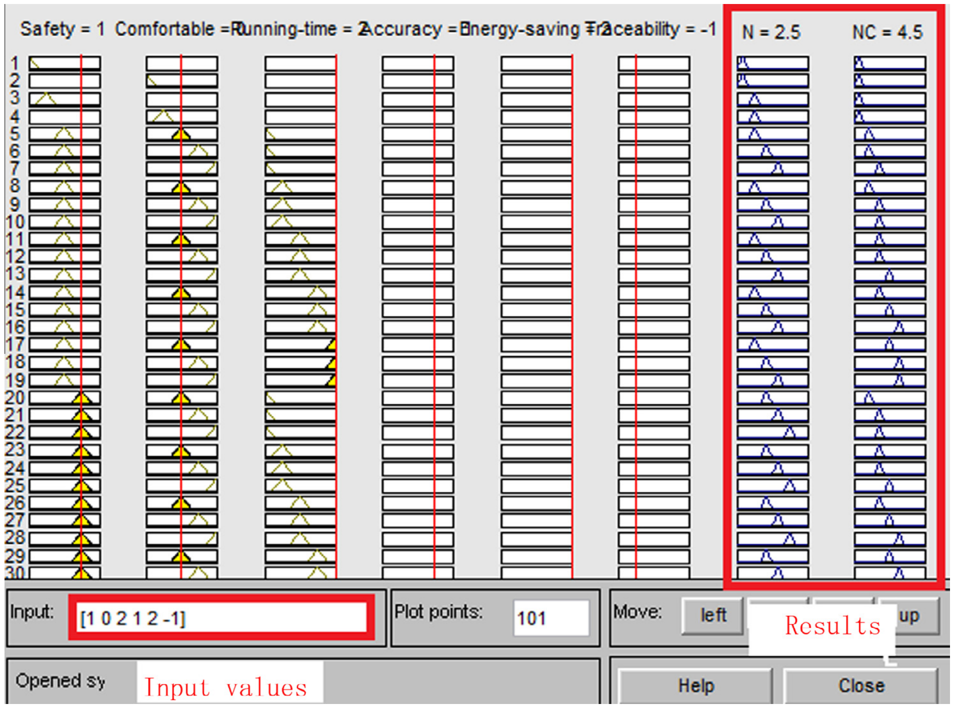

Fig. 5. The simulation results.

where, ωj is the j value in the output discourse domain, $u_{cj(\omega j)}$ is the corresponding membership value.

In the last, the results should be adjusted by the scale factor K to guarantee the control accuracy.

9. Analysis

9.1. Establish the control system

The fuzzy control system is developed in the Matlab system, its structure shows that six input variables and two output variables in the system combined by the fuzzy control functions. In this system, the input variable names are accuracy, comfortable, energy-saving, Running-Time, Safety, Traceability, and the output variable names are N and NC.

The discourse domain of A is $[-2,2]$, which is divided into five fuzzy subsets VB, B, M, G, VG. The membership function of each subsets is chosen as trigonometric function, parameters are $[-2\ -2\ -1.4]$, $[-1.6\ -1\ -0.4]$, $[-0.6\ 0\ 0.6]$, $[0.4\ 1\ 1.6]$, $[1.4\ 2\ 2]$, respectively.

Other parameters of C, E, R, S, T, N and NC are similar to parameters in A, therefore they are combined in Table 6 as follows. The word "ibid" in Table 6 expresses that the content in this space is the same as the above space.

The fuzzy rules are defined in the system, as shown in Fig. 1 below. Each rule has been input into the system using the special characteristics. There are total 81 rules for the six input two output fuzzy control system.

As shown in Fig. 1, each rule has the calculate rule using the logical operation, such as "and", "not", "or", "then". These rules are corresponding to the above expert experiences and knowledge.

9.2. System debugging

The rule viewer window can help us to debug the high speed railway fuzzy control system. The surface viewer figure is shown in Fig. 2.

We can debug the output variables by inputting some parameters in the viewer window. For example, we choose the Safety, Running-time and the output variable N as the research objects. The relationship between these three parameters is shown in Fig. 3.

According to Fig. 3, the control value N is effected by the Running-time and Safety. When we need more Safety, the N value should be changed into bigger ones. These results are corresponding to the expert experiences and knowledge. Fig. 4 expresses the relationship between Comfortable, Safety and output NC.

As shown in Fig. 4, when the passengers need more comfortable riding, the control value NC is much bigger, for it is complex for the operation. The above relationship between input variables and output variables indicate that, the fuzzy control can achieve ideal effects and given goals.

9.3. Analysis

Select 30 group different data randomly, and then input these data to the high speed railway fuzzy control system. The simulation results are listed in Table 7.

There are two parts in Table 7, the input parameters and the output parameters. The input values are chosen randomly from the domain $[-2,2]$. The output values are calculated by the fuzzy controller and shown in the table. The corresponding result figure is shown in Fig. 5 as follows.

In Fig. 5, we choose the 20th data to do the analysis process and the input value is $[1\,0\,2\,1\,2\,-1]$. After the simulation calculation, the output results are N = 2.5, NC = 4.5. Then according to the quantified relationship above we can obtain that, the high speed railway train need to accelerate into "Medium low speed". The result is correct according to the expert experiences and knowledge.

10. Conclusions

This paper proposed a fuzzy control system in the high speed railway system. The high speed railway is a giant project combined multidisciplinary, multi-field, and high new technologies together. The control system of high speed railway is important in the rail operation process. This thesis introduced the basic theory of fuzzy control and expert knowledge, and then proposed a new fuzzy control system after the analysis of the combination of fuzzy control system. The detail simulation is calculated in the Matlab software. The simulation results indicated that the fuzzy control system is effective and accurate in the high speed railway control process. The fuzzy inference rules are corresponding to the expert experiences and knowledge.

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