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# MULTI-PHASE FUZZY CONTROL OF SINGLE INTERSECTION IN TRAFFIC SYSTEM BASED ON GENETIC ALGORITHM

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Abstract. *Single intersection in the traffic system is a complex system which has the nonlinear and uncertain characteristics. If the traffic states in the single intersection become more complex, the traditional timing control of the traffic lights is not suitable for the traffic control. A multi-phase fuzzy controller of the single intersection is proposed in this paper, by using the integration of the multi-phase control, and incorporating genetic algorithm into fuzzy control design to optimize fuzzy membership functions. The proposed control method is suitable for the different traffic states in the different times, and can achieve satisfactory control performance. The simulation experiment is implemented to prove the effectiveness of the proposed multi-phase fuzzy controller.*

**Keywords:** Single intersection, Membership function, Fuzzy control, Genetic algorithm

1. **Introduction.** Single intersection is an important problem in the traffic system. The single intersection has the complex characteristics, such as the strong nonlinearity, uncertainty, and thus, it is difficult to be described by an accurate mathematical model [1]. The traditional timing control of the traffic signal light is not applied to the current traffic flow. In order to achieve the satisfactory control performance of traffic flow in the single intersection, some intelligent control methods have been developed in the traffic system. For example, Papp first used the fuzzy set theory to control the traffic flow in the intersection in 1977 [2]. Afterwards, several fuzzy control methods have been proposed for the single intersection of the traffic system [3-6]. However, in these fuzzy controllers, the fuzzy rules and membership functions are fixed and are determined only by using the experts' experience, and therefore, these traditional fuzzy controllers have some disadvantages in the traffic flow control of the single intersection. For example, if the number of the membership functions in the single intersection is large, it is difficult to determine the appropriate membership functions by using the experts' experience. Moreover, since the traffic flow is different in the different time, the fixed membership functions cannot be suitable for the variations of the traffic flow in the different time [7].

In recent years, phase sequence control is also considered in the traffic system [8-12]. The integration of the phase sequence and the intelligent control becomes one of the effective control methods to handle the single intersection problem. A multi-phase controller with two neural networks of the single intersection is proposed in [12], and the traffic flow can be controlled with the satisfactory performance. However, the initial weights of the neural networks are difficult to be determined, which makes this method difficult to be suitable for the frequent variety of the traffic flow.

In this paper, a multi-phase fuzzy control of the single intersection is proposed. In order to overcome the disadvantages of the traditional fuzzy control mentioned above, the Genetic Algorithm (GA) is utilized to optimize the membership functions in IF-THEN rules. The membership functions can be adjusted according to the traffic states in the different time, and the proposed fuzzy control is suitable for the variations of the traffic states. There are two novel and different characteristics in the proposed control method compared with the existing control methods of the single section: the integration of the multi-phase control and the fuzzy control is utilized to control the traffic flow, and the optimization of the membership functions is implemented by using GA according to the different traffic state. The satisfactory control performance of the traffic system can be obtained by using the multi-phase fuzzy control proposed in this paper. Finally, the simulation experiment is implemented to prove the effectiveness of the proposed control method.

## 2. **Initial Fuzzy Controller of the Single Intersection.**

Traffic flow distribution of the single intersection in the traffic system is shown in Figure 1. The intersection is composed of two streets that are intersected each other.

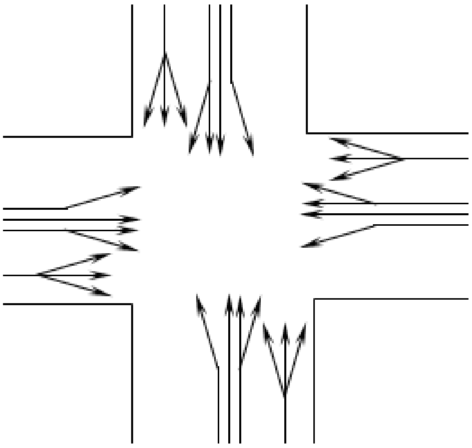

FIGURE 1. Intersection description

In this section, we designed a fuzzy controller of the intersection. In this initial fuzzy controller, the fuzzy rules and membership functions are fixed. In the next section, we used GA to optimize the membership functions of the fuzzy controller.

The structure of the fuzzy control is shown in Figure 2. There are two input linguistic variables. One is $L_i$, and the other is $L_{i+1}$. $L_i$ is the number of the delay vehicles in the current phase, and $L_{i+1}$ is the number of the delay vehicles in the subsequent phase. The output linguistic variable of the fuzzy control is $\Delta t_i$, where $\Delta t_i$ is the delay time of the green traffic light in the current phase.

The numerical values of the input and output variables are shown in Table 1. In Table 1, VS denotes the fuzzy set named very small. S denotes the fuzzy set named small. PS denotes the fuzzy set named positive small. M denotes the fuzzy set named medium. PL denotes the fuzzy set named positive large. L denotes the fuzzy set named large. VL denotes the fuzzy set named very large. The fuzzification of $L_i$ is shown in Table 2. The fuzzification of $L_{i+1}$ is shown in Table 3. The fuzzification of $\Delta t_i$ is shown in Table 4.

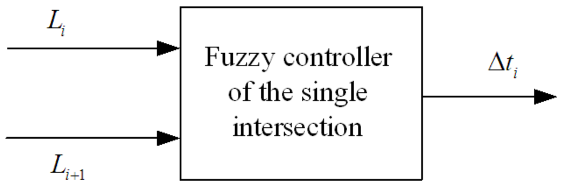

FIGURE 2. The structure of the fuzzy controller

TABLE 1. The input and output variables in the fuzzy control

| variables | domain | linguistic variables |
|---|---|---|
| $L_i$, | {0,1,2,3,4,5,6,7,8,9,10} | {VS,S,PS,M,PL,L,VL} |
| $L_{i+1}$ | {0,1,2,3,4,5,6,7,8,9,10} | {VS,S,PS,M,PL,L,VL} |
| $\Delta t_i$ | {0,1,2,3,4,5,6,7,8,9,10} | {VS,S,PS,M,PL,L,VL} |

TABLE 2. The fuzzification of $L_i$

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| VS | 1.0 | 0.9 | 0.6 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| S | 0.2 | 0.7 | 1.0 | 0.7 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0 |
| P | 0 | 0.2 | 0.8 | 1.0 | 0.8 | 0.2 | 0 | 0 | 0 | 0 | 0 |
| M | 0 | 0 | 0 | 0.1 | 0.6 | 1.0 | 0.6 | 0.1 | 0 | 0 | 0 |
| PL | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.8 | 1.0 | 0.8 | 0.2 | 0 |
| L | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.7 | 1.0 | 0.7 | 0.2 |
| VL | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.6 | 0.9 | 1.0 |

TABLE 3. The fuzzification of $L_{i+1}$

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| VS | 1.0 | 0.8 | 0.6 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| S | 0.2 | 0.7 | 1.0 | 0.8 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0 |
| PS | 0 | 0.2 | 0.8 | 1.0 | 0.7 | 0.2 | 0 | 0 | 0 | 0 | 0 |
| M | 0 | 0 | 0 | 0.2 | 1.0 | 1.0 | 0.2 | 0 | 0 | 0 | 0 |
| PL | 0 | 0 | 0 | 0 | 0.2 | 0.7 | 1.0 | 0.7 | 0.2 | 0 | 0 |
| L | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.8 | 1.0 | 0.8 | 0.2 |
| VL | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.6 | 0.9 | 1.0 |

TABLE 4. The fuzzification of $\Delta t_i$

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| VS | 1.0 | 0.8 | 0.6 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| S | 0.2 | 0.8 | 1.0 | 0.8 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0 |
| PS | 0 | 0.2 | 0.7 | 1.0 | 0.7 | 0.2 | 0 | 0 | 0 | 0 | 0 |
| M | 0 | 0 | 0 | 0.2 | 1.0 | 1.0 | 0.2 | 0 | 0 | 0 | 0 |
| PL | 0 | 0 | 0 | 0 | 0.2 | 0.7 | 1.0 | 0.7 | 0.2 | 0 | 0 |
| L | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.8 | 1.0 | 0.8 | 0.2 |
| VL | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.6 | 0.9 | 1.0 |

From Table 1, we know that there are 7 × 7 = 49 fuzzy rules in the fuzzy control. The initial fuzzy rules are determined by using the experts' experience. The initial fuzzy rules are shown in Table 5.

TABLE 5. Fuzzy rules

| $L_i$ <br> $L_{i+1}$ | VL | L | PL | M | PS | S | VS |
|---|---|---|---|---|---|---|---|
| VL | L | PL | M | PS | S | VS | — |
| L | L | PL | M | PS | S | VS | — |
| PL | VL | PL | PL | PS | PS | S | VS |
| M | VL | L | PL | PL | PS | S | VS |
| PS | VL | L | PL | PL | PS | PS | S |
| S | VL | VL | L | PL | M | PS | S |
| VS | VL | VL | L | PL | M | PS | S |

By using the singleton fuzzifier, max-min reasoning and weighted mean defuzzification [13,14], the query table of the fuzzy control can be expressed by Table 6.

TABLE 6. Query table of the fuzzy control

| $L_i$ <br> $L_{i+1}$ | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 1 | 2 | 2 | 7 | 7 | 9 | 9 | 9 | 9 |
| 1 | 0 | 3 | 4 | 4 | 5 | 6 | 7 | 8 | 8 | 9 | 9 |
| 2 | 0 | 3 | 4 | 4 | 5 | 6 | 6 | 7 | 8 | 8 | 9 |
| 3 | 1 | 2 | 3 | 4 | 4 | 5 | 6 | 7 | 8 | 8 | 8 |
| 4 | 2 | 2 | 2 | 4 | 4 | 5 | 6 | 7 | 8 | 7 | 8 |
| 5 | 1 | 1 | 2 | 3 | 4 | 4 | 5 | 6 | 7 | 7 | 8 |
| 6 | 1 | 1 | 1 | 2 | 4 | 4 | 5 | 6 | 7 | 7 | 8 |
| 7 | 0 | 1 | 1 | 2 | 3 | 4 | 4 | 4 | 6 | 6 | 7 |
| 8 | 0 | 0 | 1 | 3 | 3 | 4 | 5 | 4 | 5 | 6 | 7 |
| 9 |  | 1 | 2 | 2 | 3 | 3 | 4 | 5 | 5 | 5 | 6 |
| 10 |  | 1 | 2 | 3 | 4 | 3 | 3 | 4 | 4 | 4 | 6 |

## 3. **Optimization of the Membership Functions in the Fuzzy Controller.**

Traffic flow is varying in the different time. If the membership functions shown in Section 2 can be adjusted according to the difference of the traffic flow, the fuzzy control can be more suitable for the different traffic states, and the delay time of the vehicle in the single intersection can also be decreased.

Genetic Algorithm (GA) is a kind of artificial intelligence technology with the self-organization, self-adaptation, global searching and colony characteristics. Genetic Algorithm can find the globally optimal solution or closely optimal solution by using the colony search strategy and the information exchange between the individuals. In this section, GA is utilized to adjust and optimize the membership functions of the fuzzy control described in Section 2.

The adjustment process of the membership functions is shown in Figure 3. At first, the initial membership functions are determined by using the expert's experience. The initial fuzzy controller can also be obtained, which is described in Section 2. The initial fuzzy controller is utilized to control the traffic flow and the traffic flow parameters are storied in the historical database at the same time. After a period of time, Genetic Algorithm is utilized to optimize and update the membership functions according to the traffic flow parameters in the historical database. In the optimization process, the main steps of Genetic Algorithm include the coding scheme, generation of the initial colony, design of the fitness function, genetic manipulation.

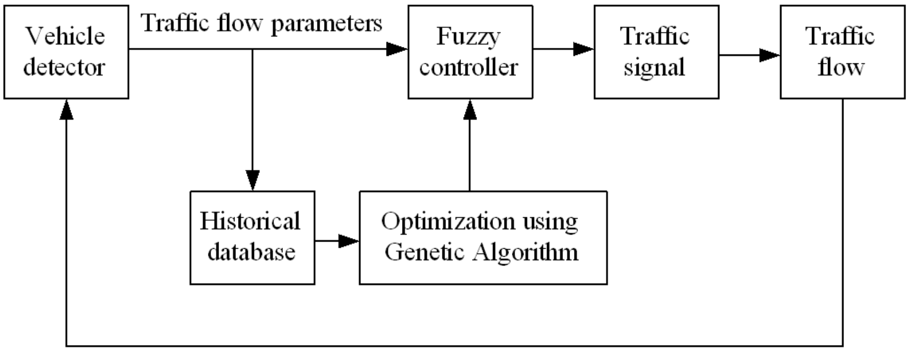

FIGURE 3. The optimization process of the fuzzy control

3.1. **Coding scheme.** Usually, for the multi-dimensional high-accuracy continuous problem, real number coding is widely utilized in Genetic Algorithm [15,16]. Its advantages are shown as follows:

1. For the membership function, real number coding is easy to decode.
2. Comparing to the binary coding, real number coding can decrease the coding length and the operation complexity.
3. Interval limit is utilized in the real number coding, which is more suitable for the fuzzy control.
4. The real number coding can express the larger value range. Contrarily, if we adopted the binary coding to express the larger value range, we must increase the coding length which can decrease the accuracy.

For the advantages of the real number coding, we utilized the real number coding in the optimization process of the membership functions.

Triangle membership functions are adopted in the fuzzy control of the single intersection. Each membership function can be expressed by its three vertices of the triangle. In this paper, $P_1$, $P_2$ and $P_3$ denote these vertices of the triangle. So, $P^\alpha = [P_1^\alpha, P_2^\alpha, P_3^\alpha]$ denote the membership function of the fuzzy set. In order to avoid the out-of-control point and overlay region in the adjacent fuzzy sets [6], we defined that each fuzzy set is into its limited region, i.e., $P_i^a \in [P_i^-, P_i^+]$ $(i = 1, 2, \cdots, n)$.

3.2. **Generation of the initial colony.** The number of colony is an important problem in Genetic Algorithm. If the number is too small, the optimization space will be reduced and the earlier convergence will be induced. If the number is too big, the computational complexity will be increased and the efficiency of Genetic Algorithm will be decreased. Usually, the number of the initial colony is $20 \sim 100$.

In this paper, the number of the initial colony is 50. From Tables 2-4, we can know that there are 56 parameters should be adjusted in the fuzzy control of the single intersection. A random matrix is given, which has 50 rows and 56 columns. The number of the rows denotes the number of the initial colony, and the number of the columns denotes the number of the coding bits.

3.3. **Design of the fitness function.** Fitness function in Genetic Algorithm can be determined according to the object function. In the optimization process of the single intersection, the object function is the delay time of the vehicles. There are two kinds of delay time in the traffic system. One is the total delay time, and the other is the average delay time [17,18].

For the multi-phases single intersection, the total delay time $D$ is:

$$D = \sum_{i=1}^{n} \bar{d}_i q_i \tag{1}$$

In Equation (1), $\bar{d}_i$ is the average delay time of each vehicle in the $i$th phase. $q_i$ is the average traffic flow in the $i$th phase.

According to the computer simulation and the actual survey of the traffic states, the computation formula of the average delay time is:

$$\bar{d} = \frac{c(1-\lambda)}{2(1-\lambda x)} + \frac{x^2}{2q(1-x)} - 0.65\left(\frac{c}{q^2}\right)^{1/3} x^{(2+5\lambda)} \tag{2}$$

In Equation (2), $\bar{d}$ is the average delay time in the appointed entrance. $c$ is the signal period. $q$ is the average traffic flow of the studied phase. $\lambda$ is the green ratio of the studied phase. $x$ is the saturation of the studied phase.

Delay expression of the intersection is:

$$D = \frac{sqR^2}{2(s-q)} = \frac{qR^2}{2(1-\lambda)} \tag{3}$$

In Equation (3), $s$ is the ratio of the arrival and departure in the saturated state.

Average delay time of each vehicle in the entrance is:

$$\bar{d} = \frac{D}{qc} = \frac{R^2}{2c(1-x)} = \frac{(1-\lambda)^2}{2(1-x)}c \tag{4}$$

$$x = \frac{q}{s} \tag{5}$$

$$\lambda = \frac{(c-R)}{c} \tag{6}$$

In Equation (4), $q$ is the vehicle arrival ratio. $R$ is the duration time of the red traffic light including the losing time. $c$ is the period.

If the vehicle arrival submits to the Poisson distribution, the average delay time of each vehicle is

$$\bar{d} = \frac{(1-g)^2}{2(1-\lambda)}c + \frac{x^2}{2q(1-x)} \tag{7}$$

In this paper, we take the average delay time of each vehicle as the object function. So, the fitness function is the inverse of the object function, which is shown in Equation (8).

$$f = \frac{1}{\bar{d}} \tag{8}$$

In Equation (8), $f$ is the fitness function.

From Equation (8), we know if the delay time of the vehicles $\bar{d}$ is small, the fitness function $f$ is big. When the optimization process is over, we can obtain the biggest fitness function, and the least delay time of the vehicles is also given.

### 3.4. Genetic manipulation.

(1) Selecting operator

By using the selecting operator, individual characteristic of the parent can be inherited to the next generation in Genetic Algorithm. So, the gene losing can be avoided, moreover, the global convergence and computational efficiency can also be increased.

There are many methods to determine the selecting operator. In these methods, fitness proportion method is widely utilized. In this selecting method, the selected probability of the individual is proportion to its fitness. The fitness proportion method is described in Equation (9):

$$P_{si} = \frac{f_i}{\sum\limits_{j}^{m} f_j} \tag{9}$$

In Equation (9), $m$ is the colony size. $f_i$ is the fitness of the $i$th individual. $P_{si}$ is the selected probability of the $i$th individual.

In Genetic Algorithm, the new individual is generated by the crossover and mutation. For the random of the crossover and mutation, the new individual may destroy the best individual of the current colony. In order to solve this problem, the selecting operator method in this paper is the combination of the fitness proportion selecting and the optimal reservation selecting. Firstly, we use the fitness proportion selecting method in the selecting process. We copy the individual structure with the highest fitness to the next colony. So, when the search process of Genetic Algorithm is finished, the finally obtained individual is the best one which has the highest fitness throughout the whole search process.

(2) Crossover operator

Genetic Algorithm uses the crossover operator to produce the new individual [19]. In this paper, the linear recombination of the real number shown in Figure 4 is adopted during the crossover process.

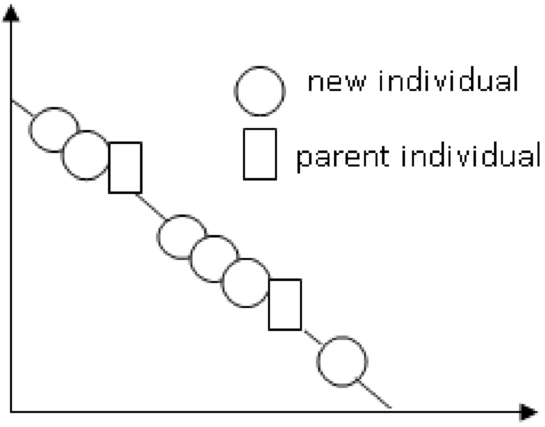

Figure 4. Linear recombination

In the linear recombination of the real number, the generation of the new individual is shown as follows:

$$\text{New individual} = \text{parent individual} + a \times (\text{parent individual} - \text{new individual}) \tag{10}$$

In Equation (10), $a$ is the proportional factor. Usually, $a$ is 0.25.

(3) Mutation operator

By using the mutation operator, Genetic Algorithm can substitute the other genes for some genes in one chromosome, and a new individual can be generated [18].

In this paper, $X^a = [x_1^a, x_2^a, \cdots, x_n^a]$ is the chromosome which is selected to participate in the mutation. The definition interval of $x_i^a$ is $[x_i^-, x_i^+]$. We assume that the mutated chromosome is $Y^a = [y_1^a, y_2^a, \cdots, y_n^a]$, then $y_i^a$ can be expressed as follows [20]:

$$y_i^a = \begin{cases} x_i^a + a\theta\left(x_i^- - x_i^+\right) & \lambda < 0.5 \\ x_i^a - \beta\theta\left(x_i^- - x_i^+\right) & \lambda \geq 0.5 \end{cases} \tag{11}$$

In Equation (11), $\alpha$, $\beta$ and $\gamma$ are the random numbers in $[0, 1]$. $\theta$ is a constant in $[0, 1]$.

## 4. **Simulation.**

### 4.1. **Simulation flow.**

We developed the simulation program based on the optimization strategy described in Section 3. The flow chart of the simulation program is shown in Figure 5.

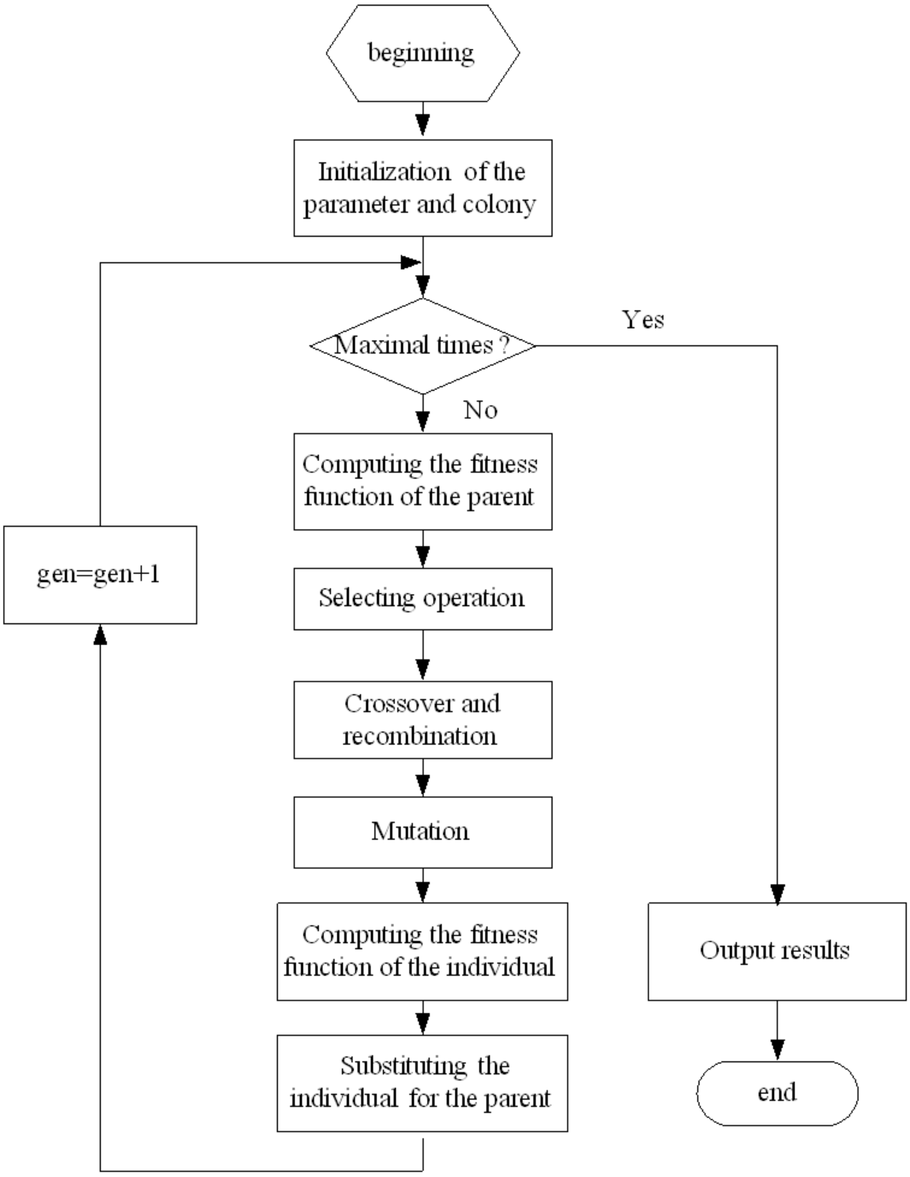

FIGURE 5. Flow chart of the simulation program

4.2. **Parameter determination in GA.**

1. N is the number of the colony. In the simulation, N = 50.
2. The initial crossover probability is 0.85. The initial mutation probability is 0.05.

In the traditional GA, the crossover probability and the mutation probability are fixed. These unchanged crossover and mutation probability can decrease the optimization performance. In this paper, the non-uniformity crossover manipulation is adopted, which can overcome the disadvantages of the unchanged crossover and mutation probability. In the first fifty times of the evolution, the crossover and mutation probability are constants. After the fifty times, the crossover probability become to be bigger and the mutation probability become to be smaller. When the evolution time is 100, both crossover probability and mutation probability are constants.

3. The final evolution time in the simulation is 120.

4.3. **Simulation results.** In the simulation, there are four phases in the single intersection. The average traffic flows in these phases are 0.38, 0.16, 0.32 and 0.20. The final results of the optimization process that denote the parameters of the membership functions are shown in Table 7. The performance curve of the average delay time during the optimization process is shown in Figure 6.

Table 7. Final optimization results of the parameters of the membership functions

| Columns | | | | | |
|---|---|---|---|---|---|
| 1-5 | 13.11 | 19.68 | 37.99 | 19.48 | 41.00 |
| 6-10 | 7.02 | 9.65 | 19.99 | 10.33 | 18.55 |
| 11-15 | 0.70 | 2.10 | 1.17 | 1.69 | 3.08 |
| 16-20 | 1.89 | 2.98 | 1.10 | 13.08 | 21.77 |
| 21-25 | 15.35 | 21.65 | 32.14 | 22.90 | 35.64 |
| 26-30 | 47.16 | 33.98 | 47.96 | 21.09 | 20.99 |
| 31-35 | 41.65 | 19.99 | 52.60 | 69.90 | 52.33 |
| 36-40 | 68.92 | 89.44 | 71.96 | 93.95 | 0.83 |
| 41-45 | 2.17 | 1.19 | 2.48 | 3.00 | 2.89 |
| 46-50 | 2.25 | 3.45 | 3.10 | 4.26 | 5.91 |
| 51-55 | 4.69 | 4.59 | 0.58 | 2.15 | 0.95 |
| 56 | 2.16 | | | | |

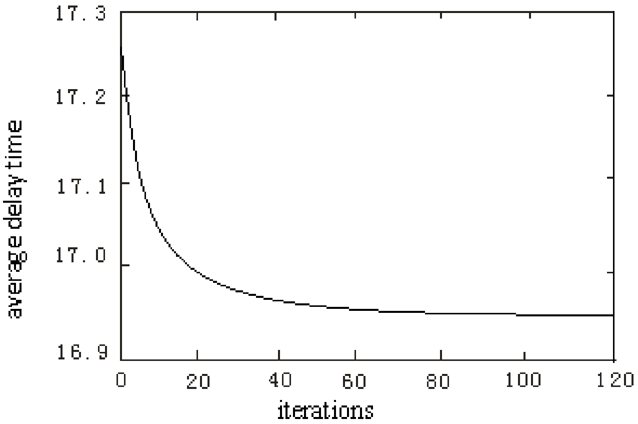

Figure 6. Performance curve of the average delay time

In the same traffic state, we adopted three methods to control the traffic flow in the single intersection. These three methods are the timing control of the traffic signal, the traditional fuzzy control and the proposed fuzzy control with the optimal membership functions in this paper. The simulation results of the control performances are shown in Table 8.

TABLE 8. Simulation results

| Sequence number of the phase | Average ratio of the arrival vehicles | Average delay time(s) | | |
|---|---|---|---|---|
| | | Timing control of the traffic signal | Traditional fuzzy control | Fuzzy control with the optimal membership functions |
| 1 | 0.38 | 25.23 | 19.30 | 17.54 |
| 2 | 0.16 | 21.32 | 17.64 | 16.11 |
| 3 | 0.32 | 24.42 | 18.99 | 17.01 |
| 4 | 0.20 | 22.98 | 18.12 | 16.65 |

If we adopted the traditional fuzzy control, the average delay time is 25.23 seconds in the first phase. If we adopted the optimized fuzzy controller, the average delay time is 17.54 seconds in the first phase. So, from Table 8, we can know that the average delay time is decreased by using the optimized fuzzy controller. Simulation results show that the combination of the fuzzy control and GA is more suitable for the changeable traffic state, and the better control performance can be obtained.

## 5. Conclusions.

Traditional fuzzy control can not be suitable for the changeable traffic state. A new multi-phase fuzzy control with the optimization of the membership functions is proposed to control the single intersection in the traffic system. By using GA, the membership functions can be adjusted according to the traffic state in the different time. The simulation experiment is implemented and proves the effectiveness of the proposed fuzzy control of the single intersection.

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