Adaptive Fuzzy Logic Traffic Signal Control Based on Cuckoo Search Algorithm

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Abstract. Traffic congestion becomes a big problem to perplex the current society. Effective traffic signal control can alleviate traffic congestion, especially for real-time traffic signal control. To improve the control efficiency, fuzzy logic control based on cuckoo search algorithm is applied to solve the problem of real-time traffic signal control. Research object is multi-lane four-phase single intersection which is also the commonly intersection in reality. Vehicular evaluation index model is established firstly. Then, the appropriate green time is given by the cuckoo search algorithm and fuzzy logic control according to the number of real-time road vehicles. Through simulation experiments, the proposed method based on the fuzzy logic control optimized by cuckoo search algorithm can be verified to obtain a good effect. This method also suits for other complex nonlinear systems.

Keywords: Fuzzy logic control · Cuckoo algorithm · Real-time traffic signal control

1 Introduction

With the development of the society, traffic jam becomes more and more serious. The effect of traffic signal control is one of the important factors for traffic jam [1]. The development of traffic signal control has experienced three stages, namely fixed-time control, induction control and adaptive traffic control. Fixed-time control method allocates green time according to the historical traffic data distribution. It is suitable for the intersections whose traffic flow change is regular, and the pattern of traffic demand is fixed. However, it will not respond to short-term changes. Induction control expands the green light time by measuring the real-time traffic arrival situation through the vehicle detector. It solves some limitations of fixed-time control to some extent, but this controller only considers extending the time of the current passing phase, while ignoring the waiting vehicles of other phases. In order to overcome this limitation, the adaptive traffic control emerges based on the present and the past traffic information using artificial intelligent control technology [2–9], such as neural networks, fuzzy logic control, various kinds of evolutionary algorithms.

Among of that, fuzzy logic control mimics human thinking and translates the expert knowledge into computable numerical data without the necessity to setup a precise mathematical model or define an exact relationship between input and output variables. It can be observed that a rapidly growing interest using fuzzy control in the field of traffic signal control [7, 10, 11]. However, the set of parameters in fuzzy logic system is extremely important to influence the effect of control. Optimizing parameters using intelligent evolutionary algorithms is one of the important way to determine the values of parameters.

Cuckoo search (CS) algorithm, also called cuckoo search, is a new heuristic algorithm put forward by Cambridge university professor Yang and Deb in 2009 [12]. The idea is based on two main strategies: the cuckoo's nest parasitic and Levy flight (Levy flights) search mechanism. By means of random walk search for an optimal bird's nest to incubate their eggs, this approach can achieve an efficient optimization model. The main advantages of CS algorithm are high global search ability, less parameters, better optimization path, high ability of multi-objective optimal problem, good generality and robustness. So, it has attracted many attentions of the scholars [13–15]. In this paper, a kind of fuzzy logic control optimized by CS algorithm is proposed to conduct the traffic signal control problem.

2   Traffic Evaluation Index Model

The most common multiple lanes single intersection is selected as study object, which has universal practical significance for its research. The intersection includes north-south straight traffic flow, north-south right-turn traffic flow, north-south left-turn traffic flow, west-east straight traffic flow, west-east right-turn traffic flow and west-east left-turn traffic flow.

Four-phase traffic signal control is adopted which is also the most common form in reality, as shown in Fig. 1, that are, "west-east straight phase", "west-east left-turn phase", "north-south straight phase" and "north-south left-turn phase".
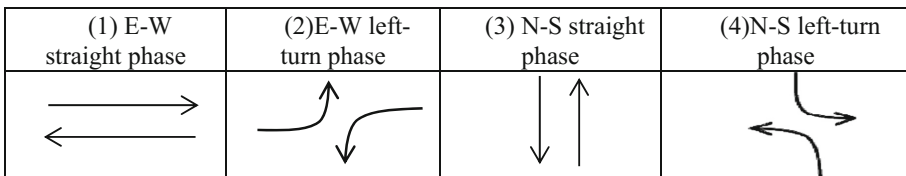

Fig. 1. Phase diagram of a four-phase signal

Suppose that the minimum successive time unit is 1 s, and two vehicles are not allowed to arrive at the same lane in a time unit. Then the number of arrived vehicles during a time unit is expressed:

$$q(i) = \begin{cases} 1, & \text{if a vehicle arrives during the } i\text{th time unit} \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

For any moment, four-phase traffic signal control contains one green phase and three red phases. Suppose V_G denotes the number of waiting vehicles at the beginning of the green phase, and V_R^1, V_R^2, V_R^3 stand for the numbers of waiting vehicles at the beginning of the three red phases respectively. So the queue lengths of the green phase and the three red phases in the nth time unit can be depicted as

$$Q_{Gn} = z * \left\{ \left\lceil (V_G + \sum_{i=1}^{n} q_i)/p \right\rceil - s * n \right\} \tag{2}$$

$$Q_{Rn}^j = \left\lceil (V_R^j + \sum_{i=1}^{n} q_i)/p \right\rceil, j = 1, 2, 3 \tag{3}$$

where p is the number of lanes; s is saturation flow rate, and $s = 1$ is supposed here; $z = 1$ if $\left\lceil (V_G + \sum_{i=1}^{n} q_i)/p \right\rceil - s * n \geq 0$, otherwise $z = 0$.

Considering the vehicles at the front of line will spend much more time to pass the intersection, so assume that the first car will spend 1.9–2.1 s, the second car will spend 1.75–1.9 s, the third car will spend 1.6–1.75 s, the fourth car will spend 1.45–1.6 s, the fifth car will spend 1.3–1.45 s, the sixth car will spend 1.15–1.3 s, the seventh car will spend 1.05–1.15 s, and the cars after the seventh car will spend 1 s. In order to facilitate the calculation of average vehicle delay, it equivalent to all cars wait for w seconds. If the number of cars in green phase is more than eight, the waiting time w should be ((0.9–1.1)*7 + (0.75–0.9)*6 + (0.6–0.75)*5 + (0.45–0.6)*4 + (0.3–0.45)*3 + (0.15–0.3)*2 + (0.05–0.15))/7 = 2.4–3.1. If the number of cars m is less than 8 vehicles in green light phase, w = (m + (0.9–1.1)*(0.75–0.9)*((m–1) + |m–1|)/2 + (0.6–0.75)*((m–2) + |m–2|)/2 + (0.45–0.6)*((m–3) + |m–3|)/2 + (0.3–0.45)*((m–4) + |m–4|)/2 + (0.15–0.3)*((m–5) + |m–5|)/2 + (0.05–0.15)   ((m–6) + |m–6|)/2)/m, (0 < m < 8), if m = 0, w = 0.

Intersection's vehicle delays can be expressed as the sum of vehicular queue length at each moment. Therefore, the vehicular delays of the current green phase and the three red phases can be expressed respectively as follows

$$D_{Gn} = \sum_{k=1}^{n} z * (V_G + \sum_{i=1}^{k} q_i - s * k * p) \tag{4}$$

$$D_{Rn}^j = \sum_{k=1}^{n} (V_R^j + \sum_{i=1}^{k} q_i), j = 1, 2, 3 \tag{5}$$

In Formula (4), $z = 1$ if $V_G + \sum_{i=1}^{k} q_i - s * k * p \geq 0$, otherwise $z = 0$. Then the total delay of the current phase is

$$D = D_{Gn} + D_{Rn}^1 + D_{Rn}^2 + D_{Rn}^3 \qquad (6)$$

For four-phase intersection, each cycle consists of four phase, so the total vehicular delay of each cycle is the sum of four phases' delay. Therefore, the total delay time during the lth cycle is

$$D^l = \sum_{x=1}^{4} D_x \qquad (7)$$

where D_x represents the total vehicular delay of the xth phase.

The total vehicular number of the current cycle is the sum of the number of waiting vehicles at the end of the last cycle and the vehicles that reach in this cycle. If q_l indicates the number of vehicles that arrive during the lth cycle, S_l stands for the number of waiting vehicles at the beginning of the lth cycle, then the average vehicular delay of the lth cycle can be expressed as

$$d_l = \frac{D^l}{q_l + S_l} \qquad (8)$$

3   Fuzzy Logic Controller for Traffic Signal Control

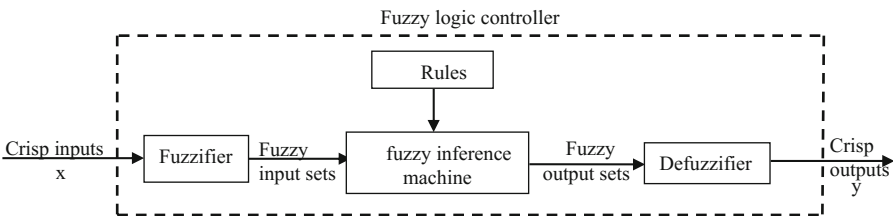The structure of fuzzy logic controller is depicted in Fig. 2.

Fig. 2. Structor of fuzzy logic controller

In the process of establishing a fuzzy logic controller, the main works are selecting membership functions and setting rule base. Gaussian membership function's curve shape is smooth. Its control characteristic is more gently. Studies have shown that it has good stability and it is a reasonable form to describe the fuzzy subset. Thus it is adopted in this paper, whose mathematical expression is:

$$\mu_{\tilde{A}}(x) = \exp(-\frac{(x-m)^2}{2\sigma^2}) \tag{9}$$

where m presents the center of the membership function, σ is the deviation of the membership function.

The membership function adopts three linguistic partitions, namely "short (S)", "medium (M)", "long (L)". For the input variable QG (QR), they stand for the short, medium and long queue length respectively, while they represent the short, medium and long green light time separately for the output variable T. let the universe of discourse be [0, 12]. According to the practical experience, the basic domain of QG (QR) is [0, 40], and the basic domain of T is [15, 65] for the straight phase and [15, 45] for the left-turn phase respectively.

The preliminary rule base is given in Table 1 on the basis of daily experience and the expert knowledge of the traffic police.

Table 1. Basic control level fuzzy rule base

T QG QR	S	M	L
S	S	M	L
M	S	M	L
L	S	S	M

4 Optimization Process with CS Algorithm

4.1 Principle of CS Algorithm

In order to simulate the habit of cuckoo, Prof. Xinshe Yang et al. assume the following three ideal states of CS algorithm:

(1) Each cuckoo lays only one egg at a time and randomly selects a nest to hatch it;
(2) In a randomly selected group of bird nests, the best one will be reserved for the next generation;
(3) The number of available as the bird's nest is fixed, the host of a bird's nest can find the probability of an exotic birds' eggs Pa ∈ [0, 1].

By assuming the above three ideal states, the updating formula of the location and path of cuckoo optimization search are as follows:

$$x_i^{(t+1)} = x_i^t + a \oplus L(\lambda), \; i = 1, 2, \ldots n \tag{10}$$

Where x_i^t refers to the position of the bird's nest in the tth generation of the ith bird nest, $\oplus$ pointing to the point multiplication, a refers to the step length control, which is used to control the step length search range, and its value obeys the normal distribution. $L(\lambda)$ is a random search path for Levy, and the random step is the Levy distribution.

$$L(s, \lambda) \sim s^{-\lambda}, (1 < \lambda \leq 3) \tag{11}$$

where s is the random step length obtained by levy flight.

It can be seen from Formula (10) that the walking mode of the line is a process of random walk. Because of the random walk characteristics of levy's flight, new solutions often appear near the local extreme points, so the short step search of levy's flight is more conducive to improving the quality of the solutions. In addition, there are new solutions at a distance from the local optimal value. Occasionally, large step length exploration makes the algorithm not easy to fall into the local extreme point.

4.2   Controller's Parameters Optimization Based on CS Algorithm

In order to obtain the optimal parameter settings, the fitness function should be set up according to the characteristics of the controlled object. The optimization problem can be converted to solve multi-dimensional function optimal value problem. For traffic control problem, the vehicular average delay at intersection is often considered as an important index for traffic control effectiveness evaluation. According to the established vehicular average delay in Formula (8), the fitness function can be defined as:

$$fitness = \min((\sum_{l=1}^{M} d_l)/M) \tag{12}$$

where M is the total number of cycles during the simulation time.

In order to reflect the real-time change of traffic flow in time, on-line optimization and adjustment is necessary, which is of great significance for the practical application of control method. We use a signal cycle as an optimization time period. The parameters after optimization are used in fuzzy controller to control the follow-up vehicles in the following time period. The control process is carried out in turn like this.

Summarize the above description, the procedure to optimize the fuzzy logic controller using CS algorithm is addressed as follows:

Step 1: Determine two input variables of the fuzzy logic controller;

Step 2: Initialize encoding for the corresponding membership functions based on the range of each parameter;

Step 3: Calculate the fitness function value of each individual;

Step 4: Carry out the corresponding operations of CS algorithm and produce new population;

Step 5: Judge whether meet the termination conditions, if satisfied, then stop the iteration algorithm. The corresponding parameters are applied to the fuzzy controller to control the vehicles in the following time period; otherwise, return to Step 3.

5 Simulation

5.1 Simulation Conditions

In order to verify the efficiency of the proposed fuzzy control method, it is compared with fixed-time control (FTC) and the traditional fuzzy logic control (FLC). The vehicular average delay and queue length under different methods are compared. According to different levels of traffic congestion, simulation experiments are set under the following six different arrival rates:

Case 1, the arrival rate of straight vehicles is 0.1 veh/s, and the arrival rate of left-turn vehicles is 0.1 veh/s.

Case 2, the arrival rate of straight vehicles is 0.2 veh/s, and the arrival rate of left-turn vehicles is 0.1 veh/s.

Case 3, the arrival rate of straight vehicles is 0.3 veh/s, and the arrival rate of left-turn vehicles is 0.1 veh/s.

Case 4, the arrival rate of straight vehicles is 0.4 veh/s, and the arrival rate of left-turn vehicles is 0.1 veh/s.

Case 5, the arrival rate of straight vehicles is 0.5 veh/s, and the arrival rate of left-turn vehicles is 0.2 veh/s.

5.2 Simulation Results and Analysis

In the above several simulation cases, the comparison results of vehicular average delay under different methods are shown in Table 2. The trend comparisons of vehicular average delay and average queue length under the fixed-time control, traditional fuzzy logic control and fuzzy control optimized by CS algorithm are shown in Figs. 3, 4, 5, 6 and 7.

Table 2. Comparison of vehicular average delay

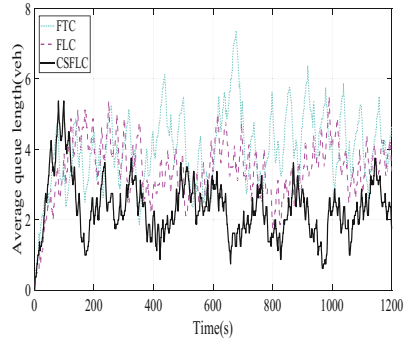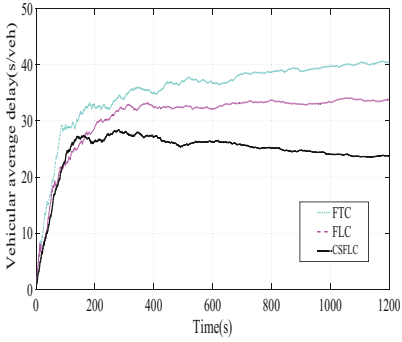| Arrival rate of the straight phase (veh/s)	Arrival rate of the left-turn phase (veh/s)	Vehicular average delay (s/veh)			Improvement compared with FTC
		FTC	FLC	CSFLC	
0.1	0.1	40.47	33.86	23.79	41.22%
0.2	0.1	43.67	40.95	34.01	22.12%
0.3	0.1	56.58	84.83	42.16	25.48%
0.4	0.1	146.30	143.85	115.11	21.32%
0.5	0.2	238.47	228.03	217.04	8.99%

Fig. 3. Vehicular average delay and average queue length comparison under Case 1
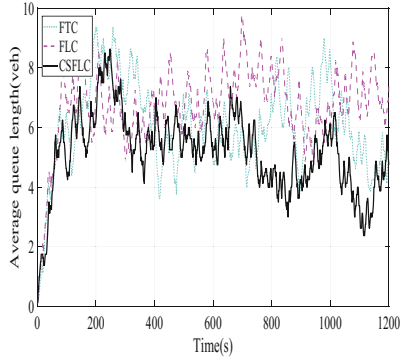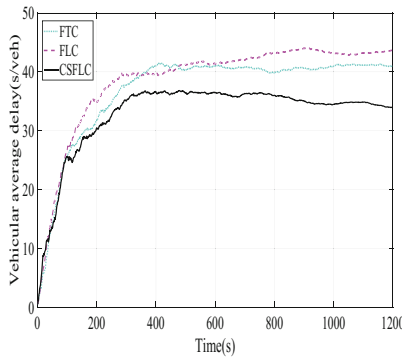

Fig. 4. Vehicular average delay and average queue length comparison under Case 2
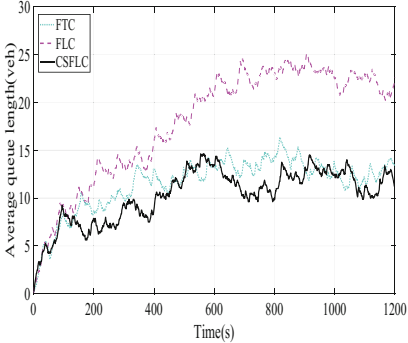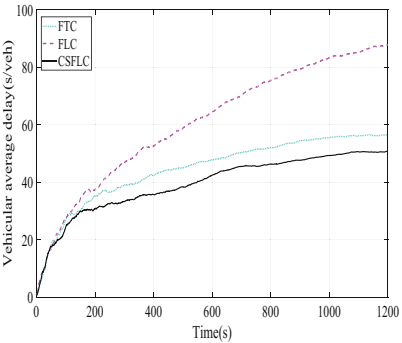

Fig. 5. Vehicular average delay and average queue length comparison under Case 3
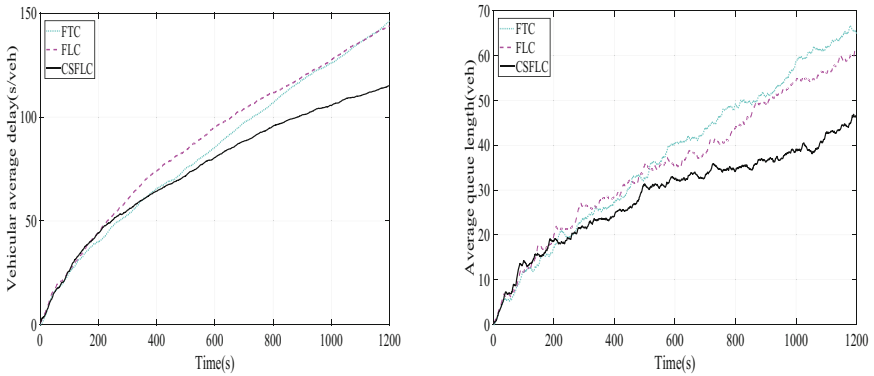
Fig. 6. Vehicular average delay and average queue length comparison under Case 4
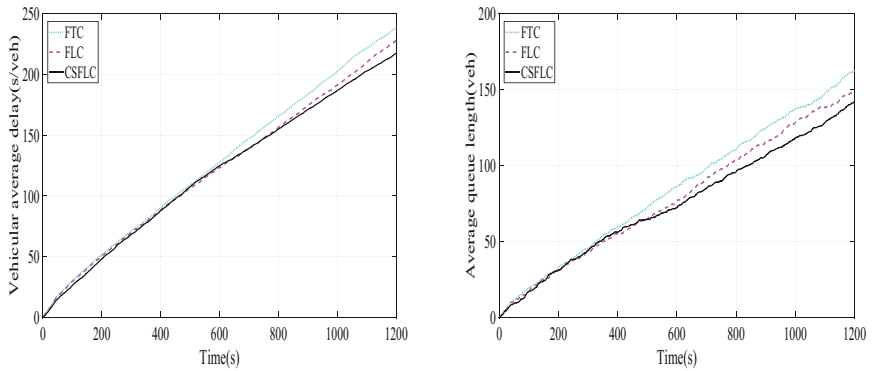

Fig. 7. Vehicular average delay and average queue length comparison under Case 5

From Table 2 and Figs. 3, 4, 5, 6 and 7, we can see that the vehicular average delays and average queue lengths under different methods also increase as the vehicular arrival rate increases. By comparing the vehicular average delays under the same arrival rate among these methods, we can see that fuzzy control method is usually better than fixed-time control method. But when the arrival rate is 0.3, the effect of fuzzy control method is worse than fixed-time control method, which illustrates the importance of parameters and the necessity of parameters optimization. However, the effect of the proposed CSFLC method is the best. When vehicular arrival rate is low (Case1–Case 2), and under slightly crowded state (Case 3–Case 4), the improvement of CSFLC can reach about 21%–41% compared with the fixed-time control. In traffic extremely congestion state (Case 5), vehicles have been far beyond the processing capacity of intersection, so if only by improving the control method at this time, the space to improve is not large, only at 8.99%. But even in this kind of condition, the proposed CSFLC method is also the most effective compared with the other two methods.

6   Conclusion

In order to effectively manage the signal control of the intersections, aiming at the common multi-lane four-phase intersection, this paper established the corresponding traffic evaluation index model, and designed a fuzzy logic controller based on the cuckoo search algorithm, and further apply the optimized fuzzy logic controller to simulate single intersection signal control. The CS algorithm possesses high global search ability, less parameters, better optimization path. It presents better searching capability and maintains diversity of the population. Compared with the fixed-time controller and the traditional fuzzy logic controller, the proposed fuzzy logic controller shows better performance. It can effectively reduce the average vehicle delay time, and alleviate traffic congestion.

It is worth to mention that the proposed method also suits for some other complex nonlinear systems, such as robot control, power systems, servo motor control, etc.

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