Study on Optimization of automatic train operation based on Grey genetic algorithm

Fan Gao¹, Fan Li², Zhe Yu²* and, Huihui Wang³

¹China Academy of Railway Sciences, Beijing 100081, China
²China Academy of Railway Sciences Corporation Limited, Beijing 100081, China
³Automotive Engineering Corporation, Tianjin 300113, China

*Corresponding author’s e-mail: right870202@163.com

Abstract. The speed controller is the kernel module of Automatic Train Operation system, and is also a key core technology of the intelligent high-speed train. The research of the intelligent speed controller of ATO system is of great significance for automatic high-speed train operation. Through the analysis of the principle and function of CTCS-3 system, the scheme of adding the speed controller of ATO system in CTCS-3 system was proposed. The connection way between the speed controller of ATO system and ground equipment was designed to realize information interaction. The model of speed controller of ATO system for high-speed trains which is researched by grey system theory was used for prediction and decision making. In the grey prediction module, the metabolic GM (1,1) model was established, and the optimal strategy was generated by the multi-objective intelligent weighted grey target decision. Finally, a reasonable control strategy of train automatic operation was obtained. The optimal control strategy was got by using genetic algorithm. Designing software for the simulation test, the simulation results show that the method achieves automatic high-speed train operation under the CTCS-3+ATO system through the actual line data, and the efficiency of train operation, the energy saving index and all the performance indexes of the train were improved.

1. Introduction

In recent years, scholars in various countries have done various researches on speed controller of high-speed train by using various methods, and have achieved certain results, such as the "predictive fuzzy control" train automatic driving system developed by Japan. [1] Singaporean scholars use genetic algorithm in the simulation of automatic train operation. [2] According to various situations, the most suitable point of idling is generated before starting, so as to achieve the lowest energy consumption. Then, a fuzzy multi-objective train automatic operation system is put forward. A new type of associative memory neural network is applied to automatic train stop in the Institute of automation of Chinese Academy of Sciences. [3] This technology realizes the long-range predictive control based on associative memory neural network in rolling optimization mode. The Railway Institute of science and technology has put forward a method based on direct fuzzy neural control, which is applied to train automatic operation control. [4] Tongji University uses fuzzy control BP network to realize inter station operation control, and uses fuzzy neural network based on genetic algorithm to realize train positioning and parking control. [5]

In this paper, the speed controller unit of the ATO system is added to the CTCS-3 level train control system, and the speed controller model is established by the grey genetic algorithm. The grey
system theory is used to design the model prediction module, correction module and decision module which generate the control strategy of train operation. The genetic algorithm is designed to optimize the train running target curve, and the whole interval control sequence is readjusted to realize the optimization control of the train.

2. Multi objective intelligent weighted grey target decision model for speed controller of high-speed train

2.1. Grey Decision-Making Module

The grey decision is made up of events, countermeasures, goals and effects. The five sub process of high-speed train operation is used as the event set of grey decision. There are 5 events.

\[ A = \{ \text{starting acceleration, steady acceleration, inert process, speed regulation braking, parking brake} \} \]

Taking the high-speed train with ten stage traction and seven stage brake as an example, it combines the train with the inert to form the countermeasure set of the speed controller of the ATO system. There are 18 countermeasures:

\[ B = \{ 10 \text{ stage traction, 9 stage traction,... 1 stage traction, inert process, 1 stage brake,... 7 stage brake} \} \]

The 4 targets of the train operation constitute the target set:

\[ K = \{ \text{punctuality, parking precision, energy consumption, comfortableness} \} \]

The Cartesian product of the event set of high-speed train and the set of countermeasures to form the situation set:

\[ S = \{ (\text{starting acceleration, 10 stage traction}), (\text{starting acceleration, 9 stage traction}),... (\text{parking brake, 7 stage brake}) \} \]

The grey decision of high speed train should take four important targets as the decision standard to find out the corresponding countermeasures of a certain event. For each goal, the best strategy is different. The effect is quantified at this time, and the best is set to 0. The best situation is found by using the grey target decision.

2.2. Multi objective grey decision matrix

In the multi-objective decision making problem, there are n alternative countermeasures to form the situation set \( S \), and \( M \) evaluation indexes to form the target set \( K \), and the effect value of the situation \( s_{ij} \) under target \( K \):

\[
u_{ij}^{(k)} \in (u_{ij}, \bar{u}_{ij}), \quad 0 \leq u_{ij} \leq \bar{u}_{ij}, t = 1, 2, \ldots, n; j = 1, 2, \ldots, m
\]

(1)

Among them, \( u_{ij}^{(k)} \) is the target value under the target \( k \); \( \bar{u}_{ij} \) is the upper critical value of the situation effect under the target \( k \); \( u_{ij} \) is the lower critical value of the situation effect under the target \( k \). The effect vector of the situation \( s_{ij} \) is obtained:

\[
u_{ij} = [u_{ij}^{(1)}, u_{ij}^{(2)}, \ldots, u_{ij}^{(m)}] \in ([u_{11}, \bar{u}_{11}], [u_{12}, \bar{u}_{12}], \ldots, [u_{im}, \bar{u}_{im}])
\]

(2)

Generally speaking, the target set \( K \) can be divided into two types, namely the benefit type and the cost type, and the corresponding grey number covering the upper bound is the best one.

2.3. Multi objective intelligent weighted grey target decision making model

The set of \( S \), which is composed of multi-objective decision plans and the target set \( K \) composed of evaluation indexes, is determined, and the grey number decision matrix of situation set \( S \) to target set \( K \) is obtained:
Among them, $\mathbf{X}$ is the grey number decision matrix.

2. The normalized grey number decision matrix is normalized for the situation set $S$:

$$
\mathbf{Y} = \begin{bmatrix} 
Y_{11}, \bar{Y}_{11} & Y_{12}, \bar{Y}_{12} & \ldots & Y_{1m}, \bar{Y}_{1m} \\
Y_{21}, \bar{Y}_{21} & Y_{22}, \bar{Y}_{22} & \ldots & Y_{2m}, \bar{Y}_{2m} \\
\vdots & \vdots & \ddots & \vdots \\
Y_{n1}, \bar{Y}_{n1} & Y_{n2}, \bar{Y}_{n2} & \ldots & Y_{nm}, \bar{Y}_{nm} 
\end{bmatrix}
$$

(4)

Among them, $\mathbf{Y}$ is the normalized grey number decision matrix; $Y_{en,m}$ is the critical value for standardizing the target situation; $\bar{Y}_{en,m}$ is the critical value for standardizing the target situation.

3. Determining the weight set of each index:

$$
W = \{w_1, w_2, \cdots, w_m\}
$$

$$
\sum_{j=1}^{m} w_j = 1, \quad j = 1, 2, \cdots, m; w_j > 0
$$

(5)

Among them, $W$ is the weight set; $w_1$ to $w_m$ is the corresponding weight of each index; $w_j$ is the weight value corresponding to any index in the train operation, and the added value of ownership is added to 1.

4. Calculate the evaluation value of the $i$ plan:

$$
\gamma_i = [\gamma_i, \bar{\gamma}_i], \quad i = 1, 2, \cdots, n
$$

(6)

Among them, $\gamma_i = \gamma_{i1} + \gamma_{i2} + \gamma_{im}$ is the lower critical value of the evaluation value; $\bar{\gamma}_i = \bar{\gamma}_{i1} + \bar{\gamma}_{i2} + \bar{\gamma}_{im}$ is the upper critical value of the evaluation value; $\gamma_i$ is the evaluation value of the plan.

5. According to the possibility of grey number and comparing the $\gamma_i$ value, we sort and select the situation in the situation.

6. Determine the bull’s eye and produce the final decision result.

3. Optimization of high speed train operation target curve by genetic algorithm

In order to solve the problem of slow speed optimization, a genetic optimization module is added to the grey speed controller. The train control sequence in the database is extracted and the quasi optimal results are calculated based on ATO performance index.

After the operation of the grey speed controller, the running record file of the train can be obtained. The record file contains detailed train control information, including the train at any time.

3.1. key point coding of high-speed train operation target curve

The key point of applying genetic algorithm is to select key points for coding in many manipulating information points. The key point is the conversion point that can best reflect the manipulation changes, which can be divided into three types.

1. Traction level position within a short distance.
2. The conversion point of traction and idle working conditions.
③ Conversion point of idle working condition and braking condition.

According to this principle, the key points selected in the operating speed distance curve obtained by the grey speed controller are shown in Figure 1.

The running record of the train can be obtained after the operation of the grey speed controller, which contains the working condition of the train at any time. The key to the final formation is a binary string, as shown in Figure 2.

![Figure 1 schematic diagram of key points selection](image1.png)

| Key Point Location Coding | Key Point Working Condition Code |
|--------------------------|---------------------------------|
| 1 0 1 0 0 0 0 0 0 0 0 0 1 0 1 1 1 0 0 0 0 |                                       |

![Figure 2 key point coding](image2.png)

The first seventeen bits store the position of the train, and the last five bits store the working condition code of the train. The first position of the working condition coding is the running condition of the train. The traction condition or inert working condition is 1, and the braking condition is 0. The last four bits are coded as the handle level. The working condition of laziness is recorded as (0000)bin.

3.2. population formation of high-speed train operation target curve

In genetic algorithm, replication and cross operation are needed. One chromosome cannot complete the optimization process. It is necessary for a certain number of individuals to form a population to evolve continuous genetic operations.

The grey speed controller generates a large number of operation records through multiple operations, selects a better running record file to generate chromosomes, and adapts the generated chromosomes to evaluate the fitness of the chromosomes. Genetic fitness is selected as the initial population. The population of 10 chromosomes can be selected to complete the optimization process.

3.3. Fitness Function of High-Speed Train

The fitness value is the criterion to judge the degree of genetic optimization. According to the performance index of ATO system, we should meet five aspects of overspeed, precision rate, parking precision, energy consumption and comfort.

It is difficult to compare five adaptations. It needs to be made up of an overall fitness function to analyze it. Because these five adaptations have different effects on the control effect, we need to add weight. As to the control effect, the overall fitness value should be reduced as far as possible. The overall fitness evaluation value is obtained.

\[
Fitness = 1 / (w_1K_{cs} + w_2K_{ad} + w_3K_{p} + w_4K_{jerk} + w_5K_{energy})
\]  

(7)
Among them, Fitness is the value of the fitness evaluation. Kcs, Kzd, Ktc, Kjerk, and Kenergy represent the fitness indexes of speed, precision, parking precision, energy consumption and comfort respectively. $w_1, w_2, w_3, w_4$ and $w_5$ are the weights corresponding to each fitness.

After calculating the fitness of genetic algorithm, the population is replicated, crossed and variant. The final optimization results are obtained according to the evaluation value of the fitness.

4. Grey genetic optimization for high speed train operation target curve

Taking the Beijing Tianjin inter city line as an example, 10 manipulating records generated by the grey speed controller are selected as the parent chromosome to form the initial population, and then the fitness values are obtained through fitness programming, and the results are shown in table 1.

| Paternal generation | Overspeed evaluation value | Punctual rate judgement value | Evaluation of parking accuracy | Comfort evaluation value | Evaluation of energy consumption | Overall fitness |
|---------------------|-----------------------------|-------------------------------|-------------------------------|--------------------------|--------------------------------|----------------|
| 1                   | 0.0                         | 159                           | 1.900                         | 2.130                    | 3432.78                        | 0.0017496      |
| 3                   | 0.0                         | 154                           | 1.700                         | 2.275                    | 3446.57                        | 0.0017487      |
| 5                   | 0.0                         | 146                           | 1.700                         | 1.837                    | 3435.79                        | 0.0017626      |
| 7                   | 0.0                         | 143                           | 1.800                         | 1.863                    | 3421.73                        | 0.0017724      |
| 8                   | 0.0                         | 132                           | 1.800                         | 1.975                    | 3445.67                        | 0.0017731      |
| 9                   | 0.0                         | 129                           | 1.800                         | 1.943                    | 3424.58                        | 0.0017865      |
| 10                  | 0.0                         | 116                           | 1.700                         | 1.864                    | 3421.73                        | 0.0018026      |

The grey speed controller produces more reasonable train operation sequence, so that the initial population stability is good, the low mutation probability is not easy to increase the population diversity, and it is easy to fall into the local extreme value and can not jump out. Therefore, according to the empirical value, after many tests, the maximum value of the range of 0.1 is chosen as the crossover probability [46,47]. Through genetic algorithm programming, the initial population is constantly optimized by genetic algorithm. After 1000 generations of optimization, the results are shown in table 2.

| Filial generation | Overspeed evaluation value | Punctual rate judgement value | Evaluation of parking accuracy | Comfort evaluation value | Evaluation of energy consumption | Overall fitness |
|-------------------|-----------------------------|-------------------------------|-------------------------------|--------------------------|--------------------------------|----------------|
| 1                 | 0.0                         | 123                           | 1.900                         | 1.932                    | 3402.69                        | 0.0018037      |
| 2                 | 0.0                         | 114                           | 1.900                         | 1.845                    | 3397.56                        | 0.0018166      |
| 3                 | 0.0                         | 107                           | 1.700                         | 2.037                    | 3417.68                        | 0.0018148      |
| 4                 | 0.0                         | 109                           | 1.900                         | 1.946                    | 3495.43                        | 0.0017749      |
| 5                 | 0.0                         | 103                           | 1.900                         | 1.845                    | 3419.05                        | 0.0018187      |
| 50                | 0.0                         | 76                            | 1.600                         | 1.846                    | 3410.63                        | 0.0018551      |
| 70                | 0.0                         | 69                            | 1.600                         | 1.836                    | 3407.58                        | 0.0018652      |
| 90                | 0.0                         | 63                            | 1.700                         | 1.903                    | 3398.32                        | 0.0018773      |
| 200               | 0.0                         | 54                            | 1.500                         | 1.809                    | 3387.53                        | 0.0018945      |
The results of the 1000 generation evolution shown in table 2 are as follows:

| Speed  | Overspeed | Parking | Punctuality | Comfort | Energy | Overall |
|--------|-----------|---------|-------------|---------|--------|---------|
| 600    | 0.0       | 34      | 0.700       | 1.698   | 3269.14| 0.0019888 |
| 800    | 0.0       | 16      | 0.600       | 1.684   | 3165.05| 0.0020795 |
| 1000   | 0.0       | 17      | 0.600       | 1.693   | 3177.65| 0.0020699 |

Overspeed indicator: no speeding. Parking accuracy index: from an average of 1.76 to 0.600. Punctuality index: from 140 to 17. Comfort index: from an average of 1.972 to 1.693. Energy consumption index: from an average of 3430 to 3177.65. Overall fitness: from an average of 0.0017719 to 0.0020699. By simulating the overall fitness of table 2.

In Figure 4, the starting speed of the train is 2380m, and the starting process is fast. The train runs near the target speed of 338km/h, and its optimization curve is relatively stable, which meets the requirements of comfort. The maximum running speed is 338.3km/h, and there is no overspeed. The optimized section of the target curve is inert during the three operations. Figures 3 and 4 show that the energy saving is 7.6%. It not only maintains a relatively high capacity of passing through the interval, but also reduces the energy loss. From the simulation results, we can see that the energy saving effect has improved significantly, and other indicators have also been raised in the control range.

5. Conclusion
In the train control system, a grey genetic algorithm is used to construct the speed controller model of the high-speed train. The information interaction mode between speed controller of vehicle mounted safety computer and ATO system is designed. The characteristics of the genetic algorithm is that it can get a final overall optimal solution. In the optimization process, the fitness of a certain generation group is relatively low, which is a normal phenomenon. By optimizing the information, the whole process control strategy can be adjusted to achieve the optimization of the train operation target curve.

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