Control Method of High-Speed Train Automatic Side Door Based on Gravitational Search Algorithm

1Liu Changying, 1Jin Yu, 1Guo Jidong, 1Chu Xinze and 2Wang Tianhao
1College of Instrumentation and Electrical Engineering, Jilin University, Changchun, 130061, China
2College of Automotive Engineering, Jilin University, Changchun, 130061, China

Corresponding Author: Wang Tianhao, College of Automotive Engineering, Jilin University, Changchun, 130061, China

ABSTRACT

The EMU has many characteristics, such as fast, safe, environmental protection and so on, which make it become the main means of transportation. Automatic side door is the channel for passengers pass in and out cars, is the most frequently used parts of passengers, the reliability and ease of its functions is closely related to with the passengers. In this study, aiming at the EMU automatic side door environment of the actual use and application characteristic, we propose a side door automatic optimization control method based on gravitational search algorithm for the optimal control of automatic side door. Firstly, this study analyzes the operating characteristics of the automatic side door and provides the basis for system control. Then, it establishes a mathematical model of the system control according to the rotating speed characteristic and torque characteristics of system drive device motor and then, the motor was controlled by optimizing PID control algorithm and PID parameters were optimized and solved by gravitational search algorithm. Finally, the proposed controlling method was verified by experiments, experimental results were shown that the method was feasible and could meet the precise control requirements of the automatic door of EMU.

Key words: EMU, automatic side door, PID, gravitational search algorithm

INTRODUCTION

China is a country in the world that has the longest high-speed railway mileage, so it is a big country of high-speed railway in the world. To achieve forward from high-speed railway big country to high-speed railway powerful country, a breakthrough must be obtained in high-speed rail vehicle design and manufacturing (Liu, 2010). Compared with conventional rail vehicles, high-speed EMU not only enhance the speed greatly but also require more and more serious in electrification, automation and intelligence and so on (Duman et al., 2010).

The side door is the connecting door between compartments in the high-speed train and is the channel for passengers passing in and out cars and is the most frequently used parts of passengers, therefore the practicability, comfort, reliability and safety of its functions are closely related to the passengers. To meet the requirements of high-speed train automatic side door and deal with the operating environment with high vibration, high noise and electromagnetic interference. In this study, a side door automatic optimization control based on gravitational search algorithm is proposed, to solve the optimization control problem (Nasir et al., 2012). In this study, aiming at the EMU automatic side door environment of the actual use and application characteristic, we propose a side door automatic optimization control method based on gravitational search algorithm for the optimal control of automatic side door.
MATERIALS AND METHODS

Automatic side door system: The EMU automatic side door system mainly consists of controller (Liu, 2010), DC motor with reducer, photoelectric encoder, drive mechanism and door shown in Fig. 1. When the system is running, the controller receives the opening signal and drives the DC motor rotating in accordance with the requirements for opening the door through the passing of the reducer and the transmission mechanism, the running speed of the door and the location of the door are detected by the photoelectric encoder connected with the DC motor, the controller controls the door running according to the contrast between the photoelectric encoder feedback information and the settings information.

The automatic side door opening or closing process is mainly divided into starting, high-speed running, deceleration running stage, low-speed running and stopping. Starting stage requires smooth and small overshoot. High-speed running stage requires a constant speed and the speed fluctuation is small. Deceleration running stage requires fast response and small overshoot. Low-speed running stage requires a constant speed and the braking process should be quick. When side door system is running, the impact of the system power supply voltage fluctuation and the transmission structure differences and the door quality differences and other factors are inevitable, the DC motor drive control must to be optimized in order to meet the control requirements of automatic side doors. The automatic side door operating characteristics is shown in Fig. 2.

System control model: Because the DC motor provides the driving force for the automatic side door system of EMU, the DC motor optimizing control is the automatic side door control core. Aiming the performance requirements for the operation of the automatic side door and combining with the features of automatic side door, the optimal control model of automatic side door system is established (Moghaddas et al., 2010).
**DC motor rotation speed model:** DC motor rotation speed \( n \) can be expressed as Eq. 1 with motor supply voltage \( U \), armature circuit resistance and air-gap magnetic flux \( \Phi \):

\[
n = \frac{U - IR}{C_e \Phi}
\]  

(1)

In the equation, \( I \) is total current of armature circuit, \( C_e \) is EMF constant. Equation 1 indicates that the motor rotation speed can be controlled by controlling the armature voltage, increasing armature circuit resistance and decreasing magnetic flux. To achieve the optional control of the automatic side door, the motor rotation speed is controlled by the means of optimizing control the voltage load on the motor armature (Tutkun and Maden, 2010).

According to the operating characteristics of the automatic door, the open/close operation process of automatic side doors is require the forward/reverse control of motor to achieve. In this study, full bridge bipolar drive circuit is adopted to realize motor drive control as shown in Fig. 3.

The voltage load on the motor armature can be expressed as:

\[
U = \left( \frac{t_1 - \frac{T - t_1}{T}}{T} \right) U_s = (2\alpha - 1)U_s
\]  

(2)

In the equation, \( U_s \) is supply voltage, \( T \) is PWM cycle and \( \alpha = \frac{t_1}{T} \) is a positive voltage output time-the duty cycle. According to the formula adjusting the voltage load on the motor armature can achieve the control of motor rotation speed. The wave of control voltage is shown in Fig. 4.

The motor is transferred, when \( \alpha > 0.5 \) and \( U > 0 \). The motor is transferred in the maximum rotation speed, when \( \alpha = 1 \) and \( U = U_s \). The motor is reversed, when \( \alpha = 0 \) and \( U = -U_s \). The motor is reversed in the maximum rotation speed when \( \alpha = 0.5 \) and \( U = 0 \). Motor does not turn, when and alternating current flowing in the motor armature, making motor armature coil generates a

![Fig. 3: Principle of full-bridge bipolar drive](image-url)
high-frequency oscillation to overcome the static friction of the load and improve the dynamic characteristics of the system. Substitute Eq. 2 into 1 so motor rotation speed can be obtained (Li and Zhou, 2011):

\[ n = \frac{(2\alpha - 1)U_s - IR}{C_\alpha \Phi} \]  

(3)

Motor torque model: After the DC motor is energized, current flows through the armature winding, the current carrying conductor in a magnetic field generate the electromagnetic torque and the rotation of the motor drag the machine under the effect of the electromagnetic torque. Motor output torque mainly includes no-load output torque, the torque to overcome the resistance movement and horizontal movement of the door.

Rated output torque of the motor \( T_{out0} \) can be expressed as:

\[ T_{out0} = 9.55 \frac{P}{n_0 i} \]  

(4)

In the equation, \( P \) is the motor rated data, \( n_0 \) is the motor rated speed, \( i \) is the reducer reduction ratio.

The output torque \( T_{out1} \) to overcome the resistance movement \( F \):

\[ T_{out1} = 9.55 \frac{VF}{\eta n_{out}} \]  

(5)

where, \( V \) is the door speed, \( n_{out} \) is the motor output speed, \( \eta \) is the transmission mechanism efficiency.
The output torque $T_{out2}$ of the motor for moving the side door, which mass is $m$:

$$T_{out2} = \frac{365mgV^2}{375n_{out}^2} \frac{dn_{out}}{dt}$$  \hspace{1cm} (6)

DC motor output torque is:

$$T_{out} = T_{out0} = T_{out1} = T_{out2}$$  \hspace{1cm} (7)

Substitute the Eq. 4, 5, 6 into 7, we can obtain the output torque of the DC motor:

$$T_{out} = 9.55 \frac{P}{n_{i}} + 9.55 \frac{VF}{\eta n_{out}} + \frac{365mgV^2}{375n_{out}^2} \frac{dn_{out}}{dt}$$  \hspace{1cm} (8)

**System control model:** The electromagnetic torque of DC motor $T$ can be expressed as in Eq. 9 with electromagnetic torque constant $C_T$:

$$T = C_T \Phi I$$  \hspace{1cm} (9)

Rotating speed characteristic equation can be obtained when substitute Eq. 9 into 3:

$$n = \frac{U_i}{C_T \Phi (2\alpha - 1)} - \frac{R}{C_T \Phi C_T \Phi} T$$  \hspace{1cm} (10)

The motor in this study contain a reducer, assuming that there is no efficiency loss between motor and reducer, set the reducer reduction ratio as, reducer output rotational speed $n_{out}$ and output torque $T_{out}$ can be expressed as:

$$n_{out} = in$$  \hspace{1cm} (11)

$$T_{out} = \frac{T}{i}$$  \hspace{1cm} (12)

Mixing Eq. 9-12, we can get the system transfer function model.

Suppose $B_i(0 \leq i \leq n)$ represents a group of rectangular structural elements, $B_i$ represents a square structure with $2i+1$ in diameter, $i = 0, 1, 2, ..., n$, then the multi-scale gradient operator is defined below:

$$n_{out} = -k_0 + k_i(2\alpha - 1)U_i - k_1F - k_i m \frac{dn_{out}}{dt}$$  \hspace{1cm} (13)

Where:

$$k_0 = -\frac{9.55RPi}{C_T C_T \Phi^2 n_0}$$
According to the Eq. 13, the power supply voltage, the movement resistance, the door mass and the motion acceleration are the main factors affecting the motor speed. The motor speed can be controlled by adjusting the duty cycle.

**Automatic side door optional control method:** In the case of the system motor and door are determined, the system transfer function can be obtained. The amount of the input control of the transfer function is the duty cycle \( \alpha \). The output rotational speed is related with system supply voltage \( U_p \), door running resistance \( F \), door mass \( m \) and the acceleration of running door \( \frac{dn}{dt} \). Due to the factors of outside interference and differences of system voltage, door running resistance and door mass is inevitable, when EMU is running, this study achieve optimal control of the automatic side door by PID optimizing control algorithm based on gravitational search algorithm.

**Incomplete differential incremental PID algorithm:** Due to the fact that the outside interference is inevitable to make it run in accordance with the requirements set for us to optimize control it. That is optimizing for DC motor control, DC Motor speed PID control algorithm, due to the sampling period of the incremental is very small, differential is particularly sensitive to data errors and noise, once the interference appears, differential will increase abruptly. In order to effectively suppress the disturbance from interference to the system, this study adds low-pass links based on incremental PID algorithm, achieving optimal control of the motor by incomplete differential incremental PID (Duman and Maden, 2011; Xu et al., 2012).

The formula of incomplete differential incremental PID is:

\[
\Delta u_n(k) = K_p[e(k) - e(k-1)] + K_i e(k) + K_d[e(k) - 2e(k-1) + e(k-2)] + \alpha \Delta u_n(k-1)
\]

where, \( K_p \) is a proportional coefficient, \( K_i \) is the integral coefficient, \( K_d \) is the differential coefficient, \( e(k) \) is the deviation of the k-th sampling time, \( e(k-1) \) is the deviation of the k-1-th sampling time (Nasri et al., 2007; Allaoua et al., 2009). The control process using incomplete differential incremental PID algorithm is shown in Fig. 5. With the analysis of the control process, determining the PID coefficients is the core of the control. In this study, we use gravitational search algorithm to determine the control coefficient.
PID based on gravitational search algorithm: H Gravitational Search Algorithm (GSA) is a new meta-heuristic searching algorithm based on Newton’s law of universal gravitation (Duman et al., 2010). In laws of gravity and mass interaction, the gravitational force between two particles is directly proportional to the product of their masses and inversely proportional to the square of the distance between them. They pull each other the gravitational attraction force and this force induces the movement of all agents globally towards the agents with heavier masses. In GSA, each mass has four particulars: its position, inertial mass, active gravitational mass and passive gravitational mass. The position of the mass equaled to a solution of the problem and its gravitational and inertial masses are specified using a fitness function (Rashedi et al., 2009, 2011; Yin et al., 2011).

The structure chart of optimal PID control based on GSA is shown as Fig. 6. The parameters of PID $K_p$, $K_i$, $K_d$ are determined by GSA.

Fig. 5: Flowchart of the PID program
Fig. 6: Parameters of PID based on GSA algorithm

The parameters of PID based on GSA algorithm can be summarized following steps.

- **Initialization:** When it is assumed that there is a system with 30 masses, 3 dimensions that on behalf of $K_p$, $K_i$, $K_d$, position of the $i$-th mass is described as follows. At first, the positions of masses are fixed randomly. So, the $i$-th mass can be expressed as Eq. 15:

$$X_i = (x_i^1, x_i^2, x_i^3) \quad i = 1, 2, \ldots, 30$$  \hspace{1cm} (15)

where, $x_i^j$ is the position of the $i$-th mass in $j$-th dimension.

- **Fitness evaluation of all agents:** When it is assumed that there is a system with 30 masses, 3 dimensions that on behalf of $K_p$, $K_i$, $K_d$, position of the $i$-th mass is described as follows. At first, the positions of masses are fixed randomly. So, the $i$-th mass can be expressed as Eq. 15

In this step all particles are dealt with, best and worst fitness are computed at each iteration described as follows:

$$\text{best}(t) = \min_{j \in \{1, \ldots, 30\}} \text{fit}_j(t)$$  \hspace{1cm} (16)

$$\text{worst}(t) = \max_{j \in \{1, \ldots, 30\}} \text{fit}_j(t)$$  \hspace{1cm} (17)

where, $\text{fit}_j(t)$ is the fitness of the $j$-th agent of iteration $t$, best ($t$) and worst ($t$) are best (minimum) and worst (maximum) fitness of all agents.

In this step, the fitness function $\text{fit}_j(t)$ is:

$$\text{fit}_j(t) = \text{rt} \times 0.1 + \frac{\sum_{i=1}^{\text{time}} (e(i))^2}{\text{time}}$$  \hspace{1cm} (18)
where, \( r_{time} \) is the rise time of this PID process, \( \left( \sum_{i=1}^{\text{time}} (e(i))^2 \right) \) is the root-mean-square error in this PID process, where, \( e(i) \) is the error of each point, \( \text{time} \) is the time of loops in PID process

- **Compute the gravitational constant** \( G(t) \): The gravitational constant of the \( t \)-th iteration is described as follows:

\[
G(t) = 100 \exp\left(-20 \frac{t}{200}\right)
\]  

(19)

where, 100 is the initial of gravitational constant, 20 is a constant, \( t \) is the current iteration and 200 is the total iteration number

- **Update the gravitational and inertial masses**: In this step, the gravitational and inertial masses are updated for each agent at iteration as follows:

\[
M_{ai} = M_{pi} = M_{ii} = M_i, \quad i = 1, 2, ..., 30
\]

(20)

\[
m_i(t) = \frac{\text{fit}_i(t) - \text{worst}(t)}{\text{best}(t) - \text{worst}(t)}
\]

(21)

\[
M_i(t) = \frac{m_i(t)}{\sum_{j=1}^{30} m_j(t)}
\]

(22)

where, \( \text{fit}_i(t) \) is the fitness of the \( i \)-th agent at iteration \( t \), \( M_{ai} \) is the active gravitational mass of the \( i \)-th agent, \( M_{pi} \) is the passive gravitational mass of the \( i \)-th agent, \( M_{ii} \) is the inertia mass of the \( i \)-th agent, \( M_i(t) \) is the mass of the \( i \)-th agent at iteration

- **Calculate the total force**: The total force acting on the \( i \)-th agent \( (F^d_i(t)) \) is calculated as follows:

\[
F^d_i(t) = \sum_{j \in \text{best}(i)} \text{rand} \cdot F^d_{ij}(t)
\]

(23)

where, \( r \) and \( j \) is a random number between interval \([0,1]\) and \( \text{best} \) is the set of first \( K \) agents with the best fitness value and biggest mass. \( F^d_{ij} \) is the gravitation from the \( j \)-th mass to the \( i \)-th mass in the dimensionality \( d \). \( F^d_{ij} \) in iteration \( t \) can be describe as:

\[
F^d_{ij}(t) = G(t) \frac{m_i(t) \times M_{ai}(t)}{R_{ij}(t) + \varepsilon} \left( x_i^d(t) - x_j^d(t) \right)
\]

(24)

where, \( R_{ij}(t) \) is the Euclidian distance between \( i \)-th and \( j \)-th agents \(| |X_i(t), X_j(t)||_2 \) and \( \varepsilon \) is the small constant
Calculate the acceleration and velocity: The acceleration and velocity of the i-th agent at iteration t in d-th dimension are calculated through law of gravity and law of motion as follows:

\[ v_i^d(t + 1) = r_i \times v_i^d(t) + a_i^d(t) \]  
\[ a_i^d(t) = \frac{F_i^d(t)}{M_i(t)} \]

where, \( r_i \) and \( i \) is the random number between interval \([0,1]\)

Update the position of agents: The next position of the i-th agents in d-th dimension are updated as follows:

\[ x_i^d(t + 1) = x_i^d(t) + v_i^d(t + 1) \]

Repeat: Steps 2-7 would be repeated until the iterations reach the criteria. In the final iteration, the algorithm returns the value of positions of the corresponding agent at specified dimensions. This value is the global solution of the optimization problem.

RESULTS

To test the feasibility of the method for controlling automatic side door in this study and the performance of the control system, an experiment with a device shown in Fig. 7 is carried out. The main performance parameters of the DC motor: rated voltage DC 24 V, rated current 4.5 A, rated power 94.7 W, rated rotate speed 3350 r min^{-1}, reduction ratio 1:10, the pitch diameter of transmission gear 105 mm, the mass of door 50 kg.

In the voltage from 16.8-36 V, the adjust time \( t_s \) is no more than 0.25 sec, the rise time \( t_r \) is no more than 0.12 sec and the overshoot \( \sigma \% \) is no more than 8.2\%. As shown in Fig. 8 and 9. The
experiment curves of opening process speed and closing process speed showed that the control method presented in the study could adapt to the operating condition change such working voltage, load, frictional resistance and so on and hold better dynamic performances and steady state performances.

**DISCUSSION**

Compare the automatic door control method in this study and the existing methods. In literature a conventional digital PID control algorithm is used (Yang et al., 2008), in which method the weight of the door, the orbit of the friction and the difference of transmission mechanism is not adding up. So the door operating speed is instability and stability control is not good. Comparing the automatic door control method in this study with the existing methods in literature (Liu et al., 2014; Ge et al., 2011; Shi et al., 2011; Liu et al., 2010; Gong et al., 2013), the operating conditions, such as the operating voltage range and the dynamic performance index such as rise time, overshoot, adjust time in this system are better than that in the existing literature. The control method presented could fully meet the reality control require of the high-speed train automatic side door.
CONCLUSION

The control system of automatic side door designed in this study sends the pulse distributed PWM message output from digital signal controller dsPIC30f5015 to full bridge driving circuit to be amplified and be loaded on motor armature. Adjust the voltage by adjusting the duty cycle of the PWM message and achieve optimize controlling the speed of automatic side door by incomplete differential incremental PID algorithm.

REFERENCES


