Robotica (2022), **40**, pp. 583–598
doi:10.1017/S0263574721000692

CAMBRIDGE UNIVERSITY PRESS

RESEARCH ARTICLE

Intelligent optimal control considering dynamic posture compensation for a cantilever roadheader

Lixia Fang[1,2,*], Zhigang Liu[1] and Miao Wu[2]

[1]School of Information and Engineering, China University of Mining and Technology Yinchuan College, Yinchuan, 750011, China and [2]School of Mechanical Electronic and Information Engineering, China University of Mining and Technology (Beijing), Beijing, 100083, China
*Corresponding author. Email: 63239158@qq.com

Received: 12 November 2020; **Revised:** 10 May 2021; **Accepted:** 10 May 2021; **First published online:** 23 June 2021

Keywords: Cantilever roadheader; Dynamic spatial posture deviation; Optimal combined compensation strategy; Principal component analysis; Multi-objective particle swarm optimization; Parallel dynamic cooperative optimization.

Abstract

The control of dynamic spatial posture for cantilever roadheader is one of the vital problems for intelligent mining, which directly affect the forming quality of cutting tunnel. Therefore, this paper proposed an intelligent optimal combination compensation strategy to adjust the real-time dynamic posture of cantilever roadheader. First, based on the topological structure analysis of cantilever roadheader, the structural loop compensation model for spatial posture deviation was established. Afterward, the principal component analysis (PCA) and multi-objective particle swarm optimization (MPSO) algorithm were applied to improve the analysis speed and accuracy of posture deviation. Finally, parallel dynamic cooperative optimization (PDCO) strategy was combined to achieve the accurate adjusting of posture deviation. The actual experimental and application results indicate that the intelligent optimal combination compensation strategy proposed in the paper can significantly improve the accuracy of the cutting tunnel. The intelligent optimal compensation strategy proposed in this paper transforms the transient spatial posture deviation into structural loop compensation, and implements by parallel cooperative strategy, finally to realize the fast analysis and efficient implementation of spatial dynamic posture deviation for cantilever roadheader during cutting process. The work of this paper provides an effective reference for intelligent deep and remote underground mining, and it can also be applied to effective control of dynamic spatial posture for intelligent engineering machinery products.

1. Introduction

Up till now, the deep, long-distance, and large-span tunnel cutting is the leading-edge technology of the international tunnel field, which also becomes a technological difficulty for intelligent, efficient, and safe coal mining all over the world. According to the relevant statistics, more than 40% of mines with mining depths over 1 km are extending deeper at a speed of 8–12m per year [1]. With the increase of mining depth, the coal seam composition, coal seam fault, and other complex nonstructural cutting environments, along with complex dynamic cutting load and inertia structural factors, etc., the further deterioration of underground environment leads to the roadheader deviate from ideal cutting path easily, and then directly affects the subsequent mining, transportation, and other productions, thereby directly restricts the progress of precise intelligent unmanned mining. Therefore, the efficient researches on coal mining technology should be carried out, to ensure the accurate trajectory of cutting tunnel.

Improving the real-time cutting posture accuracy of cantilever roadheader becomes a vital problem for the development of intelligent underground mining. However, due to the real-time posture of cantilever roadheader is quite difficult to measure and control directly, the scholars have carried

© The Author(s), 2021. Published by Cambridge University Press.

https://doi.org/10.1017/S0263574721000692 Published online by Cambridge University Press

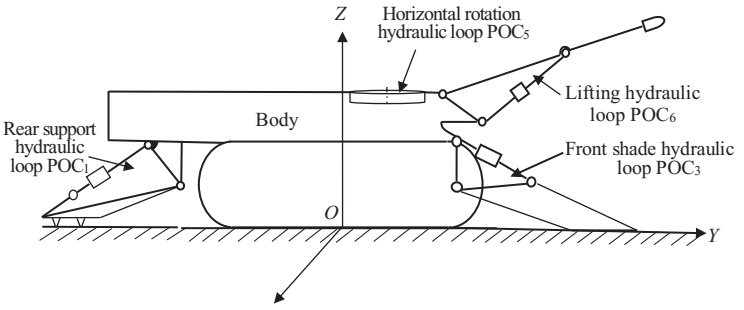


Figure 1. *Topology structure of cantilever roadheader.*

out relevant researches on this problem. Reference [2] established a mathematical model between mechanism parameters of roadheader and tunnel cross section, so as to lay a foundation for the studying of spatial posture of roadheader. Reference [3] classified the path planning problem of roadheader under unstructured environment as a general network problem, proposed the least cost modeling method, and then used genetic particle swarm optimization algorithm to optimize the path target point set, so as to provide basis for posture correction research of roadheader. In ref. [4], the parameters of cutting head are optimized according to the related rock strength, in order to obtain accurate tunnel cutting section. Based on the trajectory correction model of robot system, ref. [5] proposed an integral controller to compensate for the spatial posture of robot. Reference [6] divided the complex and closed tunnel spatial environment into regional grids and established motion model of roadheader in these grids, and then combined PID and neural network algorithm to realize the self-correction of roadheader. Reference [7] applied the genetic and mutation particle swarm optimization algorithm to optimize path target point set, so as to effectively improve the posture planning ability of roadheader. Reference [8] deduced the mathematical models of spatial posture for cantilever roadheader, and therefore provided an implementable foundation for adjusting dynamic posture. Reference [9] used different control methods (PSO and PID) to adjust the pitch angle deviation of roadheader.

Although the above researchers analyzed and provided effective methods to adjust spatial posture deviation. Nevertheless, because of the ignorance of comprehensive analysis on generation and effective engineering implementation of spatial posture deviation, the control and implement effects of spatial posture deviation have been greatly weakened. Therefore, based on the topology structure analysis of cantilever roadheader, this paper proposes a new method of compensating spatial dynamic posture deviation of roadheader by adjusting the driven parameters of structural loops. In addition, if directly applying conventional particle swarm optimization (PSO) algorithm to analyze the spatial posture deviation, there will be many disadvantages such as large amount of computation, complex solving process, and low efficiency. So, this paper proposes the principal component analysis (PCA) and multi-objective particle swarm optimization (MPSO) method to improve the analysis speed and accuracy of spatial posture deviation. Furthermore, the parallel dynamic collaborative (PDCO) servo control strategy is combined to precisely implement the posture deviation compensation for roadheader. Finally, the fast analysis and efficient implementation of spatial dynamic posture deviation for roadheader can be realized.

2. Optimal structural loop compensation model of spatial posture deviation

2.1. Spatial posture deviation

The posture deviation model is the key point to analyze spatial posture deviation for cantilever roadheader, so the EBZ-160 cantilever roadheader is chosen as a research body, and its topological structure diagram is shown in Fig. 1.

As shown in Fig. 1, the cantilever roadheader is composed of five parallel input hydraulic control loops (rear support hydraulic loop POC_1, front shade hydraulic loop POC_2, rear support front shade

https://doi.org/10.1017/S0263574721000692 Published online by Cambridge University Press

hydraulic loop POC_3, front shade-rear support hydraulic loop POC_4, and cutting arm horizontal rotation hydraulic loop POC_5) and a series hydraulic loop (cutting arm lifting hydraulic loop POC_6), the spatial trajectory of cutting head is the terminal output for cantilever roadheader. Obviously, the cantilever roadheader belongs to a typical complex engineer mechanical product with spatial multiparameter input and multiparameter output. Due to the complex cutting conditions, it is impossible to obtain the accurate dynamic motion trajectory of cutting head through direct measuring method, but according to the forward solution of mechanism, the accurate cutting trajectory of cutting head can be obtained through conversion the spatial posture of fuselage [10].

Assuming the spatial posture of fuselage for cantilever roadheader is W.

$$W = [A, L, H, \alpha, \beta, \gamma]^T \in R^{6\times 1} \tag{1}$$

where A ,L, H are the moving displacement of cantilever roadheader relative to the calibrated base point of tunnel (O-XYZ) in X, Y, Z directions, respectively, (mm). α, β, γ is the angular displacement of cantilever roadheader along X, Y, Z directions, respectively, (°). R is the spatial physical domain.

Then, the corresponding spatial posture deviation δ_W of cantilever roadheader can be expressed as follows:

$$\delta_W = \left[\delta_A, \delta_L, \delta_H, \delta_\alpha, \delta_\beta, \delta_\gamma\right]^T \in R^{6\times 1} \tag{2}$$

where $[\delta_A, \delta_L, \delta_H]^T$ are the displacement deviations (horizontal deviation, headway deviation, and top distance deviation) of cantilever roadheader. $\left[\delta_\alpha, \delta_\beta, \delta_\gamma\right]^T$ are the angle deviations (horizontal deviation, pitch angle deviation, and roll angle deviation [11]).

The classification and existence types of spatial posture deviation δ_W are listed in Table I.

Because the spatial posture of roadheader changes randomly during the actual cutting process, as shown in Table I, there are 63 types of spatial posture deviations of cantilever roadheader, and it is hard to obtain the accurate dynamic spatial posture of roadheader by direct measurement method. So, the structural loop compensation strategy is introduced to achieve the real-time and accurate control of spatial posture deviation.

2.2. Structural loop compensation model

Assuming that all the components of cantilever roadheader are ideal rigid bodies, and ignoring the deviation introduced by internal structural parameters, the spatial posture deviation is caused by dynamic loads, which becomes the main deviation for cantilever roadheader.

According to the topological relationship of spatial mechanism, the vector relationship in each closed structural loop is [12, 13]

$$l_i u_i = \sum Ta_i - b_i \tag{3}$$

where l_i represents the closed-loop i in mechanism (i=1,2,3……n). a_i represents the connection vector of each hydraulic loop. b_i represents the connection vector of each hydraulic loop in cantilever roadheader relative to tunnel bottom vector. T is the posture transformation matrix. u_i represents the radial direction vector from a_i to b_i.

The compensation model of spatial posture deviation can be obtained by taking integral operation on both sides of Eq. (3).

$$\delta_W = J_p^{-1}.\Delta l_i - J_p^{-1}.J_c.\Delta\delta \tag{4}$$

where J_p is the Jacobian vector matrix: $J_p = \begin{pmatrix} u_1^T & (Ta_1 \times u_1)^T \\ & \cdots \\ u_m^T & (Ta_6 \times u_6)^T \end{pmatrix} \in R^{6\times 6}$.

Δl_irepresents the adjustment of driving hydraulic loop (mm) ($i = 1, 2....6$).

https://doi.org/10.1017/S0263574721000692 Published online by Cambridge University Press

Table I. *Spatial posture deviation δ_W of cantilever roadheader.*

Deviation type	Deviation form	Deviation items
Single deviation (6 types)	Positional deviation	δ_A δ_L δ_H
	Angle deviation	δ_α δ_β δ_γ
Compound deviation (57 types)	Two-component deviation	$\delta_\alpha+\delta_\beta,\delta_\alpha+\delta_\gamma,\delta_\alpha+\delta_A,\delta_\alpha+\delta_L,\delta_\alpha+\delta_H,\delta_\beta+\delta_\gamma,\delta_\beta+\delta_A,\delta_\beta+\delta_L,\delta_\beta+\delta_H,\delta_\gamma+\delta_A,\delta_\gamma+\delta_L,\delta_\gamma+\delta_H,\delta_A+\delta_H,\delta_A+\delta_L,\delta_H+\delta_L$
	Three-component deviation	$\delta_\alpha+\delta_\beta+\delta_\gamma,\delta_\alpha+\delta_\beta+\delta_A,\delta_\alpha+\delta_\beta+\delta_L,\delta_\alpha+\delta_\beta+\delta_H,\delta_\alpha+\delta_\gamma+\delta_H,\delta_\alpha+\delta_\gamma+\delta_L,\delta_\alpha+\delta_\gamma+\delta_A,\delta_\alpha+\delta_A+\delta_L,\delta_\alpha+\delta_H+\delta_L,\delta_\alpha+\delta_A+\delta_H,\delta_\beta+\delta_\gamma+\delta_A,\delta_\beta+\delta_\gamma+\delta_L,\delta_\beta+\delta_\gamma+\delta_H,\delta_\beta+\delta_A+\delta_L,\delta_\beta+\delta_H+\delta_L,\delta_\beta+\delta_H+\delta_A,\delta_\gamma+\delta_A+\delta_L,\delta_\gamma+\delta_H+\delta_L,\delta_\gamma+\delta_H+\delta_A,\delta_L+\delta_H+\delta_A$
	Four-component deviation	$\delta_\alpha+\delta_\beta+\delta_\gamma+\delta_A$ $,\delta_\alpha+\delta_\beta+\delta_\gamma+\delta_L,\delta_\alpha+\delta_\beta+\delta_\gamma+\delta_H,\delta_\alpha+\delta_\beta+\delta_A+\delta_H,\delta_\alpha+\delta_\beta+\delta_L+\delta_H,\delta_\alpha+\delta_\beta+\delta_A+\delta_L,\delta_\alpha+\delta_\gamma+\delta_A+\delta_L,\delta_\alpha+\delta_\gamma+\delta_A+\delta_H,\delta_\alpha+\delta_\gamma+\delta_L+\delta_H,\delta_\alpha+\delta_A+\delta_L+\delta_H,\delta_\beta+\delta_\gamma+\delta_A+\delta_L,\delta_\beta+\delta_\gamma+\delta_A+\delta_H,\delta_\beta+\delta_\gamma+\delta_L+\delta_H,\delta_\beta+\delta_A+\delta_L+\delta_H,\delta_\gamma+\delta_A+\delta_L+\delta_H$
	Five-compound deviation	$\delta_\alpha+\delta_\beta+\delta_\gamma+\delta_A+\delta_L,\delta_\alpha+\delta_\beta+\delta_\gamma+\delta_A+\delta_H,\delta_\alpha+\delta_\beta+\delta_\gamma+\delta_L+\delta_H,\delta_\alpha+\delta_\gamma+\delta_A+\delta_L+\delta_H,\delta_\alpha+\delta_\beta+\delta_A+\delta_L+\delta_H,\delta_\beta+\delta_\gamma+\delta_A+\delta_L+\delta_H$
	Total deviation	$\delta_\alpha+\delta_\beta+\delta_\gamma+\delta_A+\delta_L+\delta_H$

$J_c$is the length direction vector of driving hydraulic loop:

$$J_C=\begin{pmatrix} u_1^T R_M & -u_1^T & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & u_6^T R_M & 1u_1^T \end{pmatrix} \in R^{6\times 6}$$

$\Delta\delta$is the corresponding adjustment deviation of hydraulic loop, for $\Delta\delta$ cannot be measured directly, so the structural deviation of hydraulic loops can be converted into the adjustment of driven hydraulic loops which can be easily measured and controlled.

Assuming$\Delta l_i^{'}=J_c.\Delta\delta$, then Eq. (4) can be simplified as follows:

$$\delta_w=J_p^{-1}\cdot(\triangle l_i-J_c\cdot\triangle\delta)=J_p^{-1}\cdot(\triangle l_i-\triangle l_i^{'}) \tag{5}$$

According to Eq. (5), the spatial posture deviation can be compensated by adjusting the length of driving hydraulic cylinders Δl_i in each corresponding structural loop, which can be easily measured by the inner hydraulic cylinder displacement sensor. Table II summarizes the specific compensation strategy.

(In Table II, Δl_{su}, Δl_{sh}, Δl_h, and Δl_v are the adjustment of front shade hydraulic loop POC_1, rear support hydraulic loop POC_3, horizontal rotation hydraulic loop POC_5, and lifting hydraulic loop POC_6 respectively (mm).)

https://doi.org/10.1017/S0263574721000692 Published online by Cambridge University Press

Table II. *Compensation strategy of structural loop for cantilever roadheader.*

Deviation type	Compensation strategy	Deviation type	Compensation strategy
$\pm\delta_A$	Δl_h and Δl_v	$\pm\delta_\alpha$	Δl_h or Δl_v
$\pm\delta_L$	Δl_h or Δl_v	$\pm\delta_\beta$	Δl_{sh} or Δl_{su}
$\pm\delta_H$	Δl_{sh} and Δl_{su}	$\pm\delta_\gamma$	Δl_{sh} or Δl_{su}

2.3. Optimization model

The Langrange equation of dynamics system [11] for cantilever roadheader can be established as follows:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right) - \frac{\partial T}{\partial q_i} + \frac{\partial D}{\partial q_i} + \frac{\partial V}{\partial q_i} = Q_i(t) \tag{6}$$

where t is the working time of cantilever roadheader. q_i and Q_i represent the generalized velocity and displacement of system (i=1,2,3……n). T, V, and D are the total kinetic energy, potential energy, and dissipation function of system, respectively.

Then, based on the above analysis, the optimization model of cantilever roadheader can be constructed from kinetic energy function, potential energy function, and dissipation function.

$$\min: \begin{cases} \sum \delta_w = \sum Y_i(\alpha,\beta,\gamma,A,L,H) - \sum \hat{Y}_i(\alpha,\beta,\gamma,A,L,H) \\ \sum t = t_1 + t_2 + t_3 + t_4 + t_5 + t_6 \\ \sum Q = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6 \end{cases} \tag{7}$$

$$\text{Constraints: } s.t. \begin{cases} Y_1(l_1) \in [0, 112] \\ Y_2(l_2) \in [0, 230] \\ Y_5(l_5) \in [0, 650] \\ Y_6(l_6) \in [0, 600] \end{cases}$$

In the optimization model, $Y_i(\alpha,\beta,\gamma,A,L,H)$ and $\hat{Y}_i(\alpha,\beta,\gamma,A,L,H)$ are the actual spatial posture and ideal spatial posture of cantilever roadheader, respectively. $\sum t$ are the total effective working time(s). $t_i$represent the working time of each hydraulic loop (s). $\sum Q$ are the total hydraulic controlled flow. Q_i represents the hydraulic control flow of hydraulic control loop($i = 1, 2, 3, 4, 5, 6$).

In the constraint model, $Y_i(l_i)$ are the adjust displacement function of hydraulic control loop ($i = 1, 2, 3, 4, 5, 6$).

The optimization model (7) indicates that to achieve the optimal design of overall system for cantilever roadheader, not only the structural conditions of roadheader must be satisfied. Meanwhile, the control of output posture should also be considered synchronous.

3. Intelligent optimal combined compensation strategy

3.1. PCA and MPSO structural loop compensation strategy

3.1.1. PCA analysis of spatial posture deviation

During the actual cutting process, due to the influence of complex and unknown cutting environment, transient cutting load, inertia state of cantilever roadheader itself and changes of trajectory tension, and other factors, which will lead the fuselage to vibrate, sideslip, and deviate from planned cutting trajectory. As shown in Table I, the variety of spatial posture deviations will greatly increase the difficulty to analyze and control the dynamic spatial posture deviation. Therefore, the principal component analysis (PCA) of spatial posture deviation is proposed by converting the interrelated posture deviation factors

https://doi.org/10.1017/S0263574721000692 Published online by Cambridge University Press

to linear unrelated variables through orthogonal transformation, and then the largest influential posture deviation factors can be chosen to reflect overall spatial posture deviation of fuselage.

The linear regression model of principal component [14] for spatial posture deviation is

$$\begin{cases} \delta_{W_1} = \mu_{11}\delta_A + \mu_{12}\delta_L + \mu_{13}\delta_H + \mu_{14}\delta_\alpha + \mu_{15}\delta_\beta + \mu_{16}\delta_\gamma \\ W_2 = \mu_{21}\delta_A + \mu_{22}\delta_L + \mu_{23}\delta_H + \mu_{24}\delta_\alpha + \mu_{25}\delta_\beta + \mu_{26}\delta_\gamma \\ \quad\quad \cdots\cdots \\ W_n = \mu_{n1}\delta_A + \mu_{n2}\delta_L + \mu_{n3}\delta_H + \mu_{n4}\delta_\alpha + \mu_{n5}\delta_\beta + \mu_{n6}\delta_\gamma \end{cases} \tag{8}$$

where δ_{W_i} represents the transient spatial posture deviation components of fuselage. u_{ij}represents the decision coefficient.

On the premise of keeping the principle information of each spatial posture deviation element of fuselage unchanged, the covariance matrix of fuselage posture deviation components is standardized. Then, according to the value of covariance, each deviation component can be listed in order, the first principal component (δ_{W1}), the second principal component (δ_{W2}), the third principal component (δ_{W3}) .....and the pth principal component (δ_{Wp}) of spatial posture deviation. According to Eq. (9), the top three principal deviation components with an information contribution rate of more than 80% can basically represent the characteristics of whole spatial posture deviation.

$$\frac{\sum_{i=1}^{m} \lambda_i}{\sum_{j=1}^{p} \lambda_j} \geq 0.8 \tag{9}$$

where p is the number of eigenvalues. λ_j represents the eigenvalue obtained from the correlation coefficient matrix of standardized matrix sample ($\lambda_1 \geq \lambda_2 \geq \lambda_3 ... \geq \lambda_p \geq 0$).

The PCA analysis of spatial posture deviation reduces the six-dimensional spatial posture deviations to three dimensions, so as to greatly reduce the complexity of spatial posture deviation, and provide an effective basis for adjusting the spatial posture of whole system.

3.1.2. MPSO solution of spatial posture deviation

According to the optimization model (7), the spatial posture deviation model of cantilever roadheader is a complex coupled model with multiparameter input (six-input drive hydraulic loops) and multiparameter output (six spatial posture outputs), which belongs to a typical multi-objective function optimal problem. Then based on the PCA analysis results, of real-time spatial posture deviation for roadheader, the multi-objective particles swarm optimization (MPSO) method [15] is preferred to optimize compensation for the top three principal spatial posture deviations, finally achieves the optimal structural loop compensation for cantilever roadheader

The speed and position of optimal particles can be updated continuously according to Eq. (10).

$$\begin{cases} v_{id}^{(k+1)} = wv_{id}^{(k)} + c_1 rand_1 \left(pBest_{id}^{(k)} - x_{id}^{(k)} \right) + c_2 rand_2 \left(gBest_{id}^{(k)} - x_{id}^{(k)} \right) \\ x_{id}^{(k+1)} = x_{id}^{(k)} + v_{id}^{(k+1)} \end{cases} \tag{10}$$

where d is the dimension of spatial flight particle (d= 1, 2, 3). w is the inertia weight (w is adjusted according to the results of PCA analysis). k is the current iteration number. $v_{id}^{(k)}$ represents the dimension component of iterative flight speed of particle i ($i = 1, 2, \ldots m$, m is the total number of particle swarm). c_1 and c_2 are the learning factor (c_1 adjusts the step length of searching particle flying to the best position of self and c_2 adjusts the step length of searching particle to fly toward global best position ($c_1 = c_2 =$ 0.5)).$rand_1$ and $rand_2$ are random numbers distributed in interval [0,1].

https://doi.org/10.1017/S0263574721000692 Published online by Cambridge University Press

The *n*th ($n \leq N$) iteration particle of structural loop compensation for global spatial posture deviation can be selected according to Eq. (11).

$$X_{id}^{*}(t+1) = \begin{cases} x_{id}(t+1), F(x_{id}(t+1)) < F(x_{di}^{*}(t)) \\ x_{id}^{*}(t), F(x_{id}(t+1)) \geq F(x_{di}^{*}(t)) \end{cases} \tag{11}$$

The specific procedure of MPSO is as follows:

Step 1: Based on PCA analysis results of spatial posture deviation, initializing particle population P, population size N, cycle variable $i = 0$, and starting position and speed of initial random particles.

Step 2: Substitute the initial conditions into optimization model (7) to calculate fitness function $F(\mathrm{x})$ of current spatial posture particles.

Step 3: Iterative increase, i=i+1, update the speed and position of variable particles according to Eq. (10).

Step 4: Repeat Step 2–Step 4, adjust, and iterate to find the optimal structural loop compensation parameters according to Eq. (11).

Step 5: Until reaching the termination number N, the corresponding optimal solution $X_{id}^{*}(t+1)$ would be the pareto solution of multi-objective optimization function: $X_{id}^{*}(t+1) = opt.\left\{\Delta l_{sh} \bigcap \Delta l_{su} \bigcap \Delta l_{su} \bigcap \Delta l_{su}\right\}$, which will provide real-time basis for dynamic posture deviation compensation.

3.1.3. PCA and MPSO strategy

Based on the above analysis, we combine **PCA** and **MPSO** methods to realize the effective analysis of optimal structural loop compensation scheme, as shown in Fig. 2.

3.2. PDCO servo control strategy

To achieve the optimal structural loop control of real-time spatial posture deviation for cantilever roadheader, it is not only necessary to collect, analyze, and feedback the real-time dynamic spatial posture information during cutting process, but it also needs to efficiently implement the optimal structural loop compensation strategy. Because the cantilever roadheader is a complex engineer machine with multi-disciplinary and strong coupled by mechanism, electricity, and hydraulic. Therefore, how to deal with the coupling relationships between mechanical structural and hydraulic control reasonably becomes an important point to obtain accurate output spatial posture of roadheader. Based on the minimum disturbance theory, parallel dynamic collaborative optimal (PDCO) control strategy is proposed in this paper, by combining with the results of PCA and MPSO, the controlling of spatial X/Z direction posture deviation, which directly affects the quality of cutting cross section is chosen as the main (external) feedback loop, while the Y direction posture deviation, which has less impact on quality of tunnel cross section is chosen as auxiliary (internal) feedback loop, so as to weaken the strong coupled relations of structural system, control system and implementation system [16]. Finally, the optimal efficient spatial posture control and implementation of the overall system can be realized. The principle of the PDCO strategy is shown in Fig. 3.

According to the optimization model (7) of cantilever roadheader, the PDCO optimal control model of whole system can be derived as

$$\min . \sum Q = \sum \left(\begin{bmatrix} L_{\delta_{W1}} & L_{\delta_{W2}} & L_{\delta_{W3}} \end{bmatrix} \begin{bmatrix} Q_{\delta_{W_1}} \\ Q_{\delta_{W_2}} \\ Q_{\delta_{W_3}} \end{bmatrix} \right) \tag{12}$$

https://doi.org/10.1017/S0263574721000692 Published online by Cambridge University Press

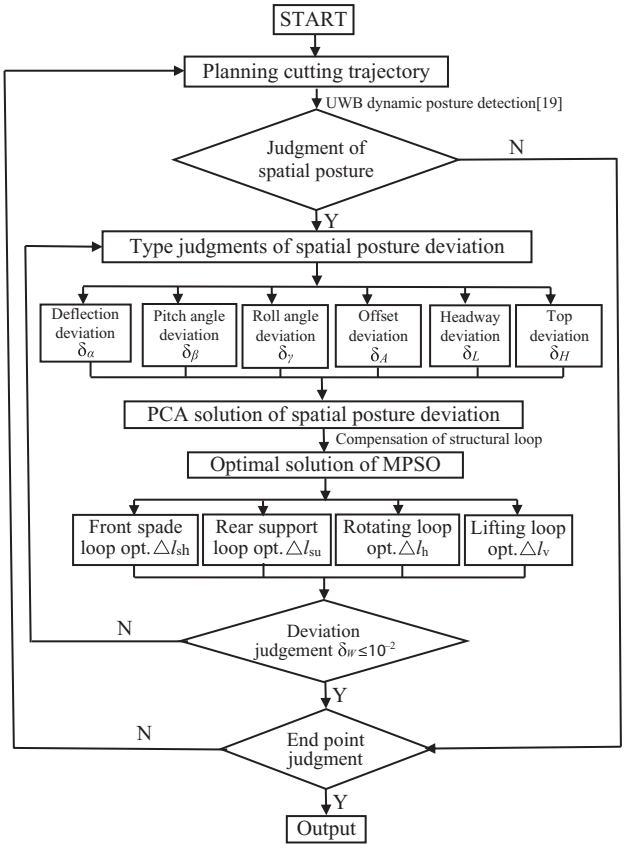


Figure 2. *PCA and MPSO analysis strategy of spatial posture deviation.*

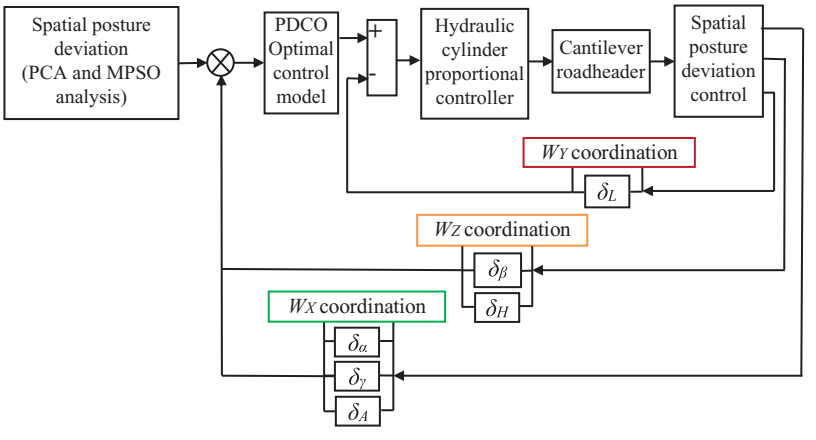


Figure 3. *PDCO control of spatial posture deviation for cantilever roadheader.*

where $\sum Q$ refers to the adjustment of overall hydraulic system. $[L_{\delta_{W1}}\ L_{\delta_{W2}}\ L_{\delta_{W3}}]$ represents the optimal structural loop compensation solution obtained by MPSO for principle spatial posture deviation component of roadheader. $\left[Q_{\delta_{W_1}}\ Q_{\delta_{W_2}}\ Q_{\delta_3}\right]^T$ represents the hydraulic compensation control flow of each according to the spatial posture deviation for roadheader .

https://doi.org/10.1017/S0263574721000692 Published online by Cambridge University Press

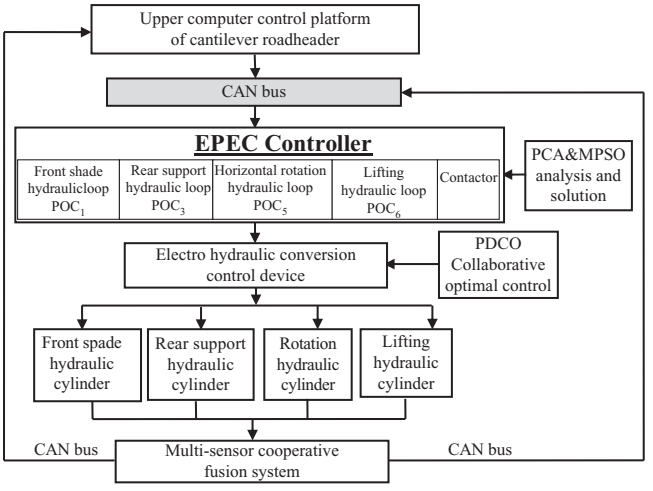


Figure 4. *Control system of cantilever roadheader.*

Considering the parallel topology pattern between rear support hydraulic loop POC_1 and front shade hydraulic loop POC_3, the series topology pattern of horizontal rotation hydraulic loop POC_5 and lifting hydraulic loop POC_6 of cutting arm, then the optimal spatial posture deviation control model of overall system can also be expressed as follows:

$$\sum Q = \left| \frac{\sum Q_{\mathrm{sh}} + \sum Q_{su}}{\sum Q_{sh} \times \sum Q_{su}} \right| + \left| \sum Q_h \right| + \left| \sum Q_v \right| \tag{13}$$

where $\sum Q_{sh}$,$\sum Q_{su}$,$\sum Q_h$,$\sum Q_v$ are the adjusting flow of corresponding hydraulic loops of POC_1, POC_3, POC_5, and POC_6, respectively (L).

Under the premise that all the constraints of the whole system are satisfied, the optimal structural loop compensation for optimal posture deviation, which is analyzed by PCA and MPSO strategy are introduced into PDCO optimal controlling models (12) or (13), finally the high-efficient parallel cooperative optimal control of spatial posture deviation for roadheader can be realized.

3.3. Control system of intelligent optimal combined compensation strategy

In order to improve the real-time controlling accuracy of spatial posture deviation for cantilever roadheader, the software adopts an intelligent combined compensation strategy (PCA and MPSO analyzing and PDCO controlling), and the hardware adopts EPEC (EPEC controller can keep working reliably and safely under high vibration frequency, wet tide, and other harsh environments with explosion-proof requirements [17]) and CAN bus control system, which can effectively avoid the disadvantages of conventional PLC control system with low protection level, poor vibration resistance, and complex structure layout [18]. The implementation system of intelligent optimal combined compensation strategy is shown in Fig. 4 (the control system of the second operation, cutting motor, and oil pump motor are omitted here).

4. The experiment

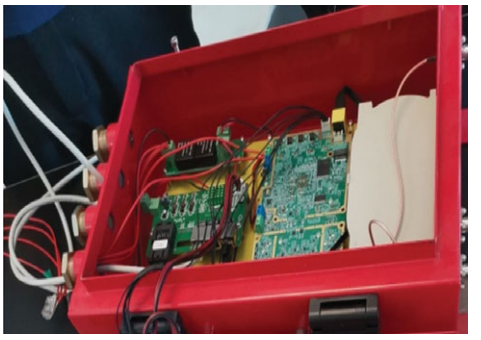
4.1. Experimental equipment

Still taking EBZ160 cantilevered roadheader as experimental basement, the intelligent operator developed by Chongqing AnKe Co., Ltd. is shown in Fig. 5 (a) and EPEC remote controller is shown in Fig. 5 (b).

https://doi.org/10.1017/S0263574721000692 Published online by Cambridge University Press



(a) Intelligent operator of cantilever roadheader



(b) EPEC remote controller

Figure 5. *Experimental equipment. (a) Intelligent operator of cantilever roadheader. (b) EPEC remote controller.*

4.2. Experimental process

The closed cutting tunnel environment is simulated, and the intelligent optimal combined compensation strategy is adopted, to carry out the comprehensive spatial dynamic posture deviation adjustment experiment of cantilever roadheader (we take the transient posture information feedback by detection device at the cutting depth D = 0.5m as an example to introduce the specific implementation process of intelligent optimal combination compensation strategy):

(1) Measurement and analysis of spatial posture deviation

The center of fuselage turntable and starting position of tunnel are calibrated, and then the instantaneous posture information of fuselage can be collected and fed back [19] (the pulse frequency is 100 ms), so the current transient spatial posture information of fuselage can be obtained as

$$\bar{X} = \frac{1}{n}\sum_{i=0}^{n} x_i = 59.52mm, \bar{Y} = \frac{1}{n}\sum_{i=0}^{n} y_i = -3874.32mm, \bar{Z} = \frac{1}{n}\sum_{i=0}^{n} z_i = 1330.15mm$$

(n is the number of measurement)

According to the forward solution of mechanism, the actual instantaneous spatial posture of cutting head can be deduced as

$$X = \bar{X}[T]_x = -1556.018mm, Y = \bar{Y}[T]_y = 94.65\text{mm}, Z = \bar{Z}[T]_z = 1825.332mm$$

(where $[T]_x$,$[T]_y$, and $[T]_z$ are the transformation matrix in X,Y, and Z directions.)

Compared to the ideal theoretical cross-section posture of cutting head: $\hat{X} = -1538mm$, $\hat{Y} = 100mm$, $\hat{Z} = 1820mm$, the transient spatial posture deviation$[\delta_W]$of fuselage can be calculated.

(2) **PCA** analysis of spatial posture deviation

The instantaneous spatial posture deviation data $[\delta_W]$ are standardized, then the correlation coefficient matrix of each deviation factor can be established, and the matrix are substituted into PCA linear regression model (8). The principal component results of instantaneous spatial posture deviation are listed in Table III.

As shown in Table III, the largest contribution rate of posture deviation component δ_{W_1} is 42.27%, and the main posture deviation variables are δ_β,δ_γ, and δ_A, with the decision coefficients are 0.6065, 0.5785 and 0.5001, respectively. The second contribution rate of posture deviation component δ_{W_2} is 30.21%, the main posture deviation variables are δ_β,δ_γ, and δ_H, the decision coefficients are 0.5508, 0.4784, and 0.1338 respectively. And the third contribution rate of posture deviation component δ_{W_3} is 20.43%, the main posture deviation variables are δ_β, δ_A, and δ_H, the decision coefficients are 0.5948,

https://doi.org/10.1017/S0263574721000692 Published online by Cambridge University Press

Table III. *PCA analysis results of transient spatial posture deviation.*

linear regression model	Contribution rate of spatial deviation component
$\delta_{W_1} = -0.5001\delta_A + 0.0741\delta_L + 0.0526\delta_H + 0.1977\delta_\alpha + 0.6065\delta_\beta - 0.5785\delta_\gamma$	42.27
$\delta_{W_2} = -0.3907\delta_A + 0.5508\delta_L + 0.4784\delta_H - 0.5292\,\delta_\alpha - 0.1309\delta_\beta + 0.1338\delta_\gamma$	30.21
$\delta_{W_3} = -0.2672\delta_A + 0.5948\,\delta_L - 0.5808\delta_H + 0.3871\,\delta_\alpha - 0.1048\delta_\beta + 0.2768\delta_\gamma$	20.43
$\delta_{W_4} = -0.0246\delta_A + 0.0434\delta_L + 0.6444\delta_H + 0.7273\,\delta_\alpha - 0.1731\delta_\beta + 0.1525\delta_\gamma$	5.21
$\delta_{W5} = -0.1630\,\delta_A - 0.2342\delta_L + 0.0479\delta_H - 0.0440\,\delta_\alpha + 0.6082\,\delta_\beta + 0.7379\delta_\gamma$	1.36
$\delta_{W6} = 0.7061\delta_A + 0.5297\delta_L + 0.1157\delta_H + 0.0088\delta_\alpha + 0.4519\delta_\beta - 0.0553\delta_\gamma$	0.5203

Table IV. *Structural loop compensation for spatial posture deviation.*

Deviation Element	Compensation scheme for structural loop
δ_β	Adjusting the front shade hydraulic cylinder to push out $\Delta l_{sh} = 19.86mm$ or adjusting rear support hydraulic cylinder to retract $\Delta l_{su} = 15.93mm$
δ_γ	Adjusting the front shade hydraulic cylinder to retract $\Delta l_{sh} = 40.12mm$ or adjusting rear support hydraulic cylinder to push out $\Delta l_{su} = 9.26mm$
δ_A	Adjusting the swing hydraulic cylinder to retract counterclockwise $\Delta l_h = 60.67$mm and synchronous adjusting the lifting hydraulic cylinder to push out $\Delta l_v = 8.72$mm

0.3871, and 0.2768, respectively. Therefore, we can conclude that the most influential transient deviation variable of overall spatial posture deviation are δ_β,δ_γ, and δ_A.

The cumulative contribution rate of the first three posture deviation principal components (δ_{W_1},δ_{W_2},δ_{W_3}) is up to 92.91%. So, the analysis and calculation of instantaneous spatial posture deviation for roadheader can be adopted according to these three deviation components.

(3) MPSO optimization

Combining with the implementation method of spatial posture deviation compensation strategy provided in Table II, and then substituting into structural loop compensation Eq. (4) (associating with the mathematical models of spatial posture deviation built in Ref. [10]), the structural loop compensation results of transient spatial posture deviation for roadheader can be solved in Table IV.

Taking the principal spatial posture deviation components (δ_β, δ_γ, δ_A) of structural loop compensation solution calculated in Table IV as initial particle, and continuously updating the iterative optimization according to Eqs. (10) and (11), and finally output the optimal particle results ($\Delta l^*_{\delta i}$) for multi-objective optimization model:

Configuration parameter of structural loop	$\Delta l^*_{\delta_{sh}}$	$\Delta l^*_{\delta_{su}}$	$\Delta l^*_{\delta_v}$	$\Delta l^*_{\delta_h}$
Optimal structural loop compensation (mm)	9.579	7.9178	60.67	8.72

The MPSO optimal solution of structural loop compensation for transient spatial posture deviation will provide the basis for implementing precise cutting.

(4) Implementation of PDCO control

Substituting the optimal posture deviation compensation results of PCA and MPSO into PDCO control model (11).

https://doi.org/10.1017/S0263574721000692 Published online by Cambridge University Press



Figure 6. *Implementation effect of combined compensation strategy (cutting depth 0.5 m).*

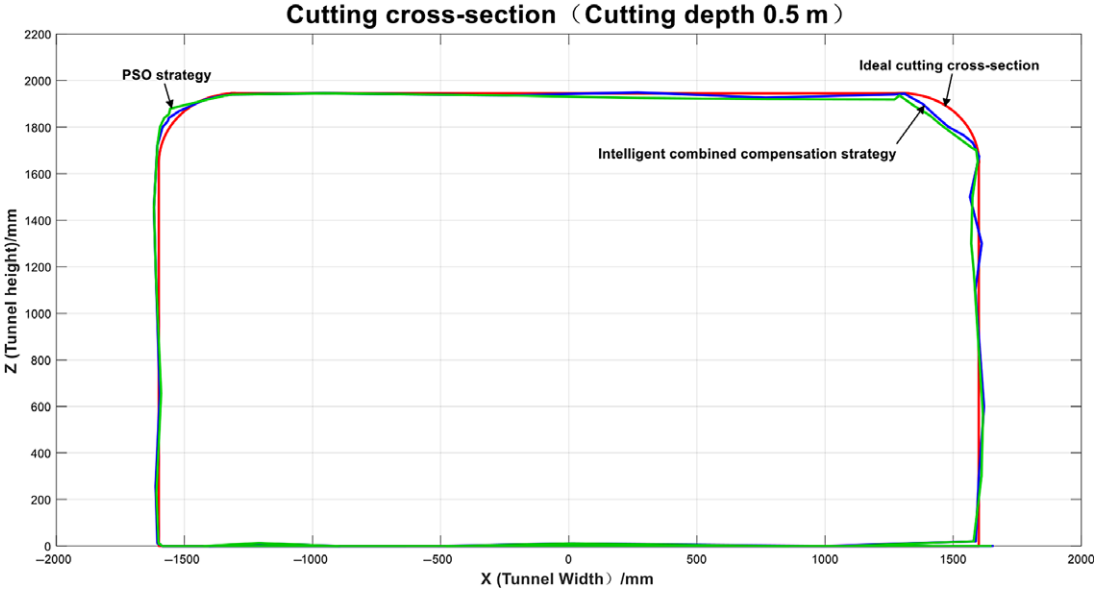


Figure 7. *Comparison between intelligent combination compensation strategy and conventional PSO strategy (the tunnel cross section with cutting depth 0.5 m).*

(5) Iterative Step (1)–Step (4), until the whole cutting of cross section with 0.5 m depth are completed as shown in Fig. 6.

To verify the implementation effect of intelligent combination strategy, the conventional PSO control strategy [8] is applied to adjust the spatial posture deviation as shown in Fig. 7.

As shown in Fig. 7, the intelligent combination compensation strategy owned a superior cross section than the conventional PSO control strategy, especially at the corner position.

https://doi.org/10.1017/S0263574721000692 Published online by Cambridge University Press

Table V. *RMSE results.*

	Controlling strategy	
Cutting depth (0.5m)	Intelligent optimal combined compensation control strategy	Conventional PSO control strategy
RMSE value	0.9536	0.9128



Figure 8. *Implement the effect of combined compensation strategy (cutting depth 1.2 m).*

The root mean squared error (RMSE) of posture regression system is used to compare the control effect of intelligent optimal combination compensation strategy and conventional PSO controlling strategy.

$$\delta_{W_{RMSE}} = \sum_{i=0}^{n} \sqrt{\left(\bar{\hat{W}}_i - \bar{W}_i\right)^2 \Big/ n} \tag{14}$$

where $\bar{\hat{W}}_i$ represents the mean theoretical posture of cross section, $\bar{W}_i$ represents the mean actual posture of cross section after controlling, n is the number of measurements.

The comparison results of RMSE are shown in Table V.

From the results in Table V, the RMSE value of intelligent optimal combined compensation strategy is more close to 1 than the conventional PSO strategy, which means that the former has a superior effect than the latter in adjusting the spatial posture of roadheader.

(6) In the same way, the intelligent optimal combined compensation control strategy is continuously applied during the subsequent cutting process, until the final cutting demand has been reached. The factual implement results are shown in Fig. 8 (cutting depth 1.2 m).

4.3. Analysis of experimental results

To qualitatively analyze the real-time control effect of combined compensation strategy of spatial posture deviation for cantilever roadheader, we measured the final cutting tunnel and used MATLAB to construct the spatial model of actual cutting tunnel, and compared it with theoretical planning cutting tunnel, as shown in Fig. 9.

As shown in Fig. 9, there are small posture deviations between actual cutting tunnel cross section and theoretical planning tunnel cross section after applying the intelligent optimal combined compensation strategy.

https://doi.org/10.1017/S0263574721000692 Published online by Cambridge University Press

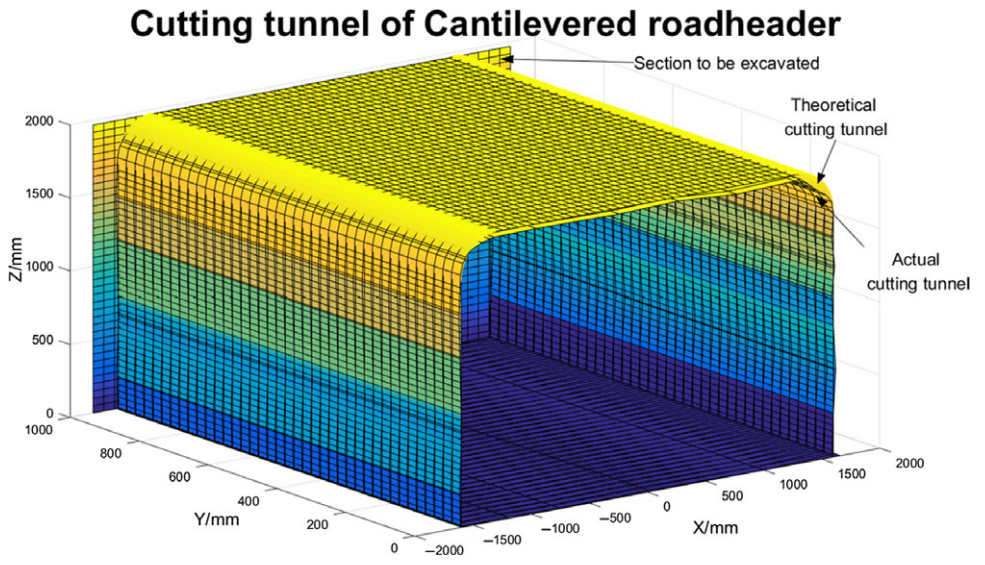


Figure 9. *Analysis model of cutting tunnel.*

Here, the spatial posture similarity S is introduced to describe the coincidence between actual simulated posture of cutting tunnel (W_s) and theoretical posture of cutting tunnel ($\hat{W}_t$).

$$S=\frac{\sum_{L=0}^{L}\bar{W}_S}{\sum_{L=0}^{L}\bar{\hat{W}}_t} \tag{15}$$

where L is the total length of cutting tunnel cross section (mm).

The value of similarity S is

$$S=\begin{cases}1 & \bar{W}_S\cong\bar{\hat{W}}\\ \dfrac{\sum_{L=0}^{L}\bar{W}_S}{\sum_{L=0}^{L}\bar{\hat{W}}_t} & \bar{W}_S\neq\bar{\hat{W}}\end{cases} \tag{16}$$

When the cross section trajectories coincide with each other, the coincidence similarity is S = 1. When the two do not coincide with each other, the value of S is between 0 and 1.

According to the experimental data and simulation results of PID controlling strategy [8], the spatial posture similarity results are listed as follows:

Spatial posture direction	**Similarity of Intelligent optimal combined compensation strategy**	**Similarity of PID control strategy**
Cutting width direction (X direction)	$S_x=\frac{\sum\bar{W}_{S_x}}{\sum\bar{\hat{W}}_{t_x}}=\frac{39.2534}{43.9420}=0.8933$	$S_x=\frac{\sum\bar{W}_{S_x}}{\sum\bar{\hat{W}}_{t_x}}=\frac{36.7116}{43.9420}=0.8354$
Cutting height direction (Z direction)	$S_x=\frac{\sum\bar{W}_{S_z}}{\sum\bar{\hat{W}}_{t_x}}=\frac{1095.35}{1188.4}=0.9217$	$S_x=\frac{\sum\bar{W}_{S_z}}{\sum\bar{\hat{W}}_{t_x}}=\frac{1022.18}{1188.4}=0.8601$

https://doi.org/10.1017/S0263574721000692 Published online by Cambridge University Press

The similarity results show that the similarity in Z direction and X direction is 0.9217 and 0.8933, respectively, which is obviously higher than that of the PID control strategy. It can be seen that the intelligent optimal combined compensation strategy proposed in this paper can effectively improve the forming quality of cross section for cantilever roadheader.

5. Conclusion

(1) Based on the structural compensation model of spatial posture deviation, the PCA method was proposed to analyze the spatial posture information, and then MPSO method was applied to quickly obtain the optimal structural loop compensation for transient spatial posture deviation of cantilever roadheader.
(2) An efficient PDCO control strategy for a complex control system of cantilever roadheader was proposed by constructing a double-layer feedback servo parallel dynamic cooperative control loop to effectively implement the structural loop compensation for spatial posture deviation of cantilever roadheader.
(3) The intelligent optimal combined spatial posture deviation compensation strategy was proposed by combining the PCA and MPSO analysis of structural loop compensation and PDCO control implementation to realize the fast analysis and efficient control of real-time spatial dynamic posture for cantilever roadheader during cutting process, and finally achieve accurate trajectory of cutting tunnel.

The intelligent optimal compensation strategy proposed in this paper has high practical application value for the realization of precise unmanned cutting for cantilever roadheader, and is also suitable for the dynamic spatial posture control for the same kind of intelligent engineering machinery products.

Acknowledgments. This work was supported by a mechanical engineering specialty construction project in Ningxia Hui Autonomous Region and construction of intelligent working robot for urban pipe gallery and general funded projects of the National Natural Science Foundation of China (2018101060080).

Author's Contribution Lixia Fang conceived and designed the study. Zhigang Liu performed the simulation and experiments. Miao Wu reviewed the paper. All authors read and approved the manuscript.

Code Availability Some data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interest The authors declare that they have no conflicts of interest.

References

[1] http://www.chinacoal-safety.gov.cn/gk/tzgg/201901/t20190109_223745.shtml
[2] G. K. Shaffer and A. Stentz, "A Robotic system for underground coal mining," *IEEE International Conference on Robotics and Automation*, (1992) pp. 633–638.
[3] X. L. Zhao, X. Y. Du, X. B. Qu and W. T. Li, "Research on automatic deviation correction technology of cantilever roadheader," Coal Min. Mach. **31**(7), 58–65 (2010).
[4] G. Liu, D. S. Mu, S. X. Duan and D. C. Song, "Design parameters optimization of cutting head of cantilever roadheader based on genetic algorithm," Appl Mech Mater 215-216, 193–196 (2012). doi:10.4028/www.scientific.net/AMM.215-216.193
[5] Y. P. Zhai, Research on Deviation Compensation Strategy of a New Four DOF Attitude Adjustment Mechanism, *Ph.D Thesis* (Tianjin University, Tianjin, China, 2015).
[6] M. J. Zhang, X. H. Cai, F. Y. Lv, K. Zong and M. Wu, "Research on self-correction of grid type roadheader in confined tunnel space," *J. Instrum.* **39**(3), 62–70 (2018).
[7] J. J. Yang, Z. H. W. Tang, X. L. W and M. Wu, "Study on the stochastic constraint environment modeling of the deviation correction path of coal roadheader," *J. Min. Sci.* **4**(1), 58–65 (2019).
[8] X. L. Ding, L. L. Zhou and J. Zhou, "Analysis method of space pose deviation of robot," *J. Beijing Univ. Aeronaut. Astronaut.* **35**(2), 241–245 (2009).
[9] M. J. Zh, F. Y. Lu, S. H. Fu, K. Zong and M. Wu, "Study on the pitch angle control of a robotized hydraulic roadheader using different control methods," *J. Mech. Sci. Technol.* **32**(10), 4893–4901 (2018).

https://doi.org/10.1017/S0263574721000692 Published online by Cambridge University Press

[10] L. X. Fang, T. Wang, Y. M. Li and M. Wu, "Research on spatial position deviation of cantilever roadheader based on topological structure analysis," *J. Coal Ind.* **11**, 3940–3951 (2020).
[11] Y. Y. Yang, D. W. J. *Dynamics of Mechanical Systems* (Tsinghua University Press, Beijing, 2009).
[12] T. L. Yang, *Topological Structure Design of Robot Mechanism* (Science Press, Beijing, 2012).
[13] P. Xie, Y. H. Du, P. T. Tian and B. Liu, "A comprehensive error compensation method for parallel robots," *J. Mech. Eng.* **48**(9), 43–49 (2015).
[14] X. Z. Han, Y. H. Zhang, F. J. Sun and S. H. Wang, "Determination method of index weight based on principal component analysis," *J. Sichuan Mil Eng* **33**(10), 124–126 (2012).
[15] C. A. Coello, G. T. Pulido and M. S. Lechuga, "Handling Multiple Objectives with Particle Swarm Optimization," IEEE Transactions on Evolutionary Computation **8**(3), (2004).
[16] L. X. Fang, T. Wang, P. J. Wang, C. H. Hou and M. Wu, "Kinematic cooperative optimization control algorithm for underground heavy-load robot," *J. Intell. Rob. Syst.* (2021). https://doi.org/10.1007/s10846-021-01360-y
[17] Shanghai peffin Automatic Control Co., Ltd. EPEC PLC set 2 (2024) controller hardware manual (2005).
[18] G. J. Xu, "Research on EPEC controller in control system of roadheader," *Coal Mine Mach.* **36**(5), 260–261 (2015).
[19] F. Shichen, L. I. Yiming, Z. O. Kai and Z. Minjun, "Accuracy analyses of UWB pose detection system for roadheader," *Chin. J. Sci. Instrum.* **38**(8), 1978–1987 (2017).

Cite this article: L. Fang, Z. Liu and M. Wu (2022). "Intelligent optimal control considering dynamic posture compensation for a cantilever roadheader", Robotica **40**, 583–598. https://doi.org/10.1017/S0263574721000692

https://doi.org/10.1017/S0263574721000692 Published online by Cambridge University Press