Research on Path Optimization for Directional Drilling in Coal Mines Based on Intelligent Algorithms

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Abstract: The underground coal mine environment is complex, and traditional drilling path planning relies on experience, leading to issues such as high target deviation rates and excessive ineffective footage. This study constructs a three-dimensional trajectory geometric model, integrates geological and engineering constraints, and proposes an improved adaptive intelligent optimization algorithm. These measures enable precise planning and efficient optimization of underground directional drilling paths, providing technical support for safe and efficient coal mine drilling.
***Keywords*:** directional drilling; path optimization; intelligent algorithm

1. Introduction

Underground coal mine drilling technology, as a crucial component of coal mining, directly impacts safety production, resource utilization efficiency, and economic benefits. The complex underground environment — characterized by high methane levels, high dust concentration, humidity, and confined tunnel spaces — demands drilling technology with enhanced precision and efficiency. Therefore, there is an urgent need to introduce intelligent algorithms to overcome the bottleneck of path optimization under multidimensional constraints, driving the development of drilling technology toward intelligent and refined advancements.

2. Current situation and challenges of underground directional drilling path planning

Due to the complex geological constraints of high gas, soft coal, and faults, the current underground directional drilling still mainly uses the "manual experience+two-dimensional profile" mode, and the trajectory adjustment is seriously lagging behind. Engineering test data shows that under this mode, the target deviation rate consistently exceeds 8%, and the average ineffective footage per hole is about 32 meters, resulting in an average extension of the construction period by more than 20% [1]. In addition, traditional path algorithms have low search efficiency when processing three-dimensional grids with millions of nodes, and are not coupled with engineering constraints such as drilling pressure and friction, resulting in insufficient drillability of planned paths. Therefore, building an intelligent path optimization method that takes into account both geological environment and engineering constraints is an urgent need to break through the bottleneck of safe and efficient drilling.

3. Three dimensional mathematical modeling of directional drilling path

To accurately describe the motion state of downhole directional drilling tools in complex coal seams, a three-dimensional trajectory geometric model was constructed using the minimum curvature method. This method assumes that the trajectory between adjacent measuring points is a spatial arc, ensuring first-order continuity of the wellbore trajectory and conforming to the elastic bending characteristics of the drill pipe. Based on incremental depth measurement ÄL , deviation angle α and azimuth angle ϕ , derive the three-dimensional coordinate increment of trajectory nodes through spatial geometric transformation, as shown in equation (1):

$$\begin{bmatrix} \Delta N \\ \Delta E \\ \Delta V \end{bmatrix} = \frac{\Delta L}{2} \cdot \frac{2}{\kappa} \tan\left(\frac{\kappa}{2}\right) \cdot \begin{bmatrix} \sin\alpha_1 \cos\phi_1 + \sin\alpha_2 \cos\phi_2 \\ \sin\alpha_1 \sin\phi_1 + \sin\alpha_2 \sin\phi_2 \\ \cos\alpha_1 + \cos\alpha_2 \end{bmatrix} \tag{1}$$

In the formula, ΔN , ΔE , ΔV are the increments of the north, east, and vertical coordinates respectively, κ and are the rate of change of the full angle (dogleg degree). To ensure that the planned path meets the engineering drillability requirements, the model introduces drilling tool passability constraints, sets a maximum dogleg degree threshold (≤4.5°/30m), and eliminates infeasible solutions with excessive curvature [2].

On this basis, the drilling operation space is finely discretized, and an environmental model is constructed using a 0.2m×0.2m×0.2m corner grid. By integrating gamma ray while drilling, resistivity, and in hole imaging data, the sequential indication simulation algorithm is used to map geological uncertainties such as faults and gas rich areas into grid traffic costs $\lambda \in [1,5]$. Further coupling the soft rod model to calculate the axial friction and torque of the drill string, constructing a comprehensive objective function that includes path length, trajectory smoothness, and geological risk cost, achieving multi-dimensional constraint coupling between geological environment and engineering mechanics, and providing a mathematical basis for intelligent algorithms to optimize calculations in discrete space.

4. Path optimization strategy for improving intelligent optimization algorithms

4.1 Node encoding of drilling trajectory based on 3D spatial meshing

To achieve digital representation of drilling trajectories in heterogeneous geological environments, a three-dimensional spatial gridding method is adopted to discretize the underground working space. Set the center of a 0.2m×0.2m×0.2m cubic grid as a candidate trajectory node, and construct an undirected graph G(V,E). using the 26- neighborhood three-dimensional Moore's connection rule. In this structure, each node is assigned a seven element attribute group containing geometric position, curvature characteristics, and mechanical state, as shown in equation (2):

$$S_i = \left\langle x_i, y_i, z_i, \kappa_i, \lambda_i, F_i, T_i \right\rangle \tag{2}$$

In the formula, κ_i is the node incidence curvature, λ_i is the geological passage cost, F_i, T_i and are the axial force and torque of the drill string at this location, respectively. To effectively compress the search space, the algorithm introduces a hierarchical hash index strategy, establishing a vertical 2m sliding window based on the trend surface of the coal seam floor, and a horizontal 1m r sliding window along the centerline of the designed roadway, retaining only the effective nodes within the window, significantly reducing the node size from 1.2×10^6 levels to 1.5×10^4 levels [3]. The specific definition and quantification range of node attributes are shown in Table 1. In the chromosome encoding stage, a variable length real string structure is used, and gene loci sequentially store node numbers and tool face angles ω, where ω is discretized with a step size of 15°. The upper limit of string length is determined by dividing the maximum depth by the grid step size, ensuring that the encoding can fully cover the target area and adapt to the dynamic extension of the drilling trajectory [4].

Table 1. Definition of Node Attributes and Parameter Range for Drilling Trajectory

Attribute Name	Symbol	Unit	Data Range	Physical Meaning and Function
Spatial Coordinates	(x,y,z)	m	Local roadway coordinate system	Determine trajectory geometry position for collision detection
Incident Curvature	κ	°/m	[0,4.5]	Characterize trajectory curvature, constrain drilling tool passability
Geological Cost	λ	Dimensionless	[1,5]	Reflect formation hardness and structural risk, guide obstacle avoidance
Axial Load	F	kN	[0,180]	Monitor drill pressure transmission efficiency, prevent buckling
Drill String Torque	T	N·m	[0,4500]	Evaluate rotational resistance, ensure drilling rig power matching

4.2 Introducing adaptive operators to enhance the global convergence capability of algorithms

In response to the problem of traditional multi-objective algorithms easily falling into local optima under complex constraints, this study introduces an adaptive control mechanism in the NSGA-III framework.Set the crossover probability P_c and mutation probability P_m as dynamic functions of population crowding and iteration process, where the adaptive adjustment model for crossover probability is shown in equation (3):

$$P_c = 0.9 - 0.4 \cdot \left(\frac{C_d}{C_{d_{max}}} \right)^{0.5} \tag{3}$$

In the formula, C_d is the crowding distance of the current generation population, $C_{d_{max}}$ and is the historical maximum crowding distance. This mechanism enables the algorithm to automatically reduce the crossover rate to retain excellent individuals when the population distribution is dense, and increase the crossover rate to expand the search boundary when it is sparse. At the same time, a monitoring threshold is set. When the gradient of congestion distance descent is less than 0.02 for five consecutive generations, it is judged to have reached a standstill, and the Gaussian Cauchy mixture mutation strategy is triggered immediately: a local Gaussian perturbation is performed with a probability of 0.7 for fine search, and a Cauchy long jump mutation is performed with a probability of 0.3 to escape the local extremum [5]. The operator configuration strategies for different stages are detailed in Table 2.

Table 2. Adaptive Evolution Operator Configuration and Trigger Strategy

Evolutionary Stage	Trigger Condition	Operator Type	Parameter Setting/Behavior Logic	Strategy Purpose
Population Diversity	$C_d / C_{d_{max}}$ >0.6	Dynamic Crossover	$P_c \in [0.5,0.65]$	Maintain population structure, prevent premature convergence
Rapid Convergence	$C_d / C_{d_{max}} \in [0.6]$	Dynamic Crossover	$P_c \in [0.65,0.9]$	Accelerate transmission of superior genes
Stagnation Escape	ΔC_d <0.02 (5generations)	Hybrid Mutation	0.7(Gaussian)+0.3(Cauchy)	Balance local exploitation and global escape
Constraint Verification	After individual generation	Physical Filtering	$\kappa \in 4.5$, $F \in 0.85$Frate	Eliminate undrillable paths, ensure engineering safety

5. Conclusion

In short, the directional drilling technology in coal mines using intelligent algorithms has broad development prospects and enormous application potential. This article achieves efficient optimization of directional drilling paths in coal mines under multiple constraint conditions through 3D modeling and improved intelligent algorithms. This method effectively improves trajectory accuracy and engineering drillability, providing new ideas for safe drilling under complex geological conditions, and has important engineering application value and promotion prospects.

References

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