Coordinated Speed Planning Strategy of Scraper Conveyor and Shearer Based on Scraper Conveyor Loads Analysis

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Abstract. In order to improve the loads stability of scraper conveyor, an integrated coordinated speed planning strategy of scraper conveyor and shearer based on scraper conveyor loads analysis is proposed to avoid impact of large load fluctuation to continuous and efficient production. The scraper conveyor loads analysis is provided as foundation of the research. Multi-objective optimization model and particle swarm optimization (PSO) algorithm are introduced and processing method based on multi-objective PSO for speed planning is established. Furthermore, a simulation example is presented and the results indicate the proposed method is outperforming traditional speed set mode. Finally, an application experiment in ground simulated fully-mechanized face is demonstrated the practical effect.

1. Introduction
Shearer, scraper conveyor and hydraulic supports are main mechanical and electrical equipment in fully mechanized coal face, and the three machines’ continuously and normally operation is key guarantee for the sequential mining related to production efficiency and economic benefits. Among them, scraper conveyor working in close conjunction with shearer is the main equipment of mine transportation system which transports coal and provides track for shearer.

In matched design of the three machines, scraper conveyor rated load is usually determined by calculated heaviest load, which leads to waste of electricity energy. What’s worse, scraper conveyor and shearer in actual operation lack speed coordination mechanism. Specifically, scraper conveyor chain speed remains constant and shearer makes some speed adjustments just based on coal-rock cutting loads condition, which would result in the load of scraper conveyor changing continuously in a wide range accompanied with shearer position, draw rate, direction and work time [1]. At this point, local pressure overloaded will be easily caused on scraper chain as rib spalling appears. Therefore, the phenomena of locked-rotor, high outage rate and heavy load starting are frequent during operation of scraper conveyor, which will impair scraper conveyor lifetime and production efficiency, resulting in additional energy consumption [2].

Although many approaches are proposed for coordinated control of coal mining machines and scraper conveyor loads analysis, they have some common disadvantages as follows [3]. Firstly, most of the coordinated control methods focus on shearer and hydraulic supports to realize position detection or attitude coupling relationship determination, but the speed of shearer and scraper conveyor are rarely considered for cooperative control field except some simple sequence control.
Secondly, several transmission mechanism of scraper conveyor are carried out just to obtain theoretical basis for structural optimization or equipment selection, meanwhile the proposed articles about scraper conveyor driving system are mainly intended to gain satisfying dynamic starting characteristics in heavy load start condition. However, the load change of scraper conveyor in whole operation process impacted by coal cutting of shearer is crucial for mining system healthy and stable operation.

In order to tackle the above problems, this paper proposes an integrated coordinated speed planning strategy of scraper conveyor and shearer based on scraper conveyor loads analysis through multi-objective PSO algorithm. The simulation example and application experiment prove the effectiveness and superiority of the proposed method.

2. Scraper Conveyor Loads Analysis

2.1. Shearer Bidirectional Mining Technology

The research present shearer bidirectional mining process in Figure 1, for it is the background technology of scraper conveyor loads analysis [4].

![Figure 1. Shearer bidirectional mining process.](image)

A certain working face and the relevant equipment are selected as research objects for detail analysis of a cycle cutting coal process, and the parameters are showed in Table 1.

| Components          | Parameters          | Symbols | Units   |
|---------------------|---------------------|---------|---------|
| Working face        | Total length       | $L$     | 200 m   |
|                     | Length of tilted-cutting | $N$   | 20 m    |
|                     | Coal density       | $\gamma$| 1.39 t/m$^3$|
| Shearer MG300/730-WD2 | Maximum draw speed | $v_{\text{max}}$ | 6 m/min |
|                     | Mining height      | $h$     | 2 m     |
|                     | Cutting depth      | $S$     | 0.63 m  |
| Scraper conveyor SGZ800/800 | Chain speed | $v_c$ | 1.81 m/s |

Then, the sequence of shearer bidirectional mining process is listed in Table 2 in accordance with Figure 1. In addition, shearer would take 2 minutes to adjust spillplate and rocker arms for reverse between two sequences which will not be repeated in Table 2.

| Sequences | Shearer actions                                                                 | Speed parameters |
|-----------|---------------------------------------------------------------------------------|------------------|
| 1         | Cut coal from upper groove to down groove at full speed                           | 6m/min           |
| 2         | Cut bottom coal remained by sequential 1, then tilted-cut whole coal seam till extreme position on down groove side | 2m/min           |
| 3         | Cut bottom coal remained by sequential 2 and then cut whole coal seam to down groove | 2m/min           |
| 4         | Cut bottom coal remained by sequential 3, then cut coal from down groove to upper groove at full speed | 6m/min           |
Cut bottom coal remained by sequential \( \odot \), then tilted-cut whole coal seam extreme position on upper groove side \( \odot \)

Cut bottom coal remained by sequential \( \odot \) and then cut whole coal seam till upper groove

2.2. Load Change Analysis of Scraper Conveyor

It can be shown in the shearer bidirectional mining sequence above that shearer in working face has two different kinds of trace, straight line and tilted-cutting S-bend, and the moving direction of shearer can be classified into up groove to down groove and the opposite [5].

(1) When shearer working in straight line segment:

If mining height \( h \), cutting depth \( S \), coal density \( \gamma \) are known, the mining quantity of shearer in unit length can be calculated as:

\[
q_s = hS\gamma \tag{1}
\]

Scraper conveyor chain speed \( v_c \) has direction constantly from tail to nose. Shearer draw speed \( v_s \) is positive when it in the same direction with \( v_c \). Otherwise, \( v_s \) is negative. Then we can express the linear density of coal loaded in scraper conveyor as below:

\[
q_c = \frac{hS\gamma v_c}{v_c - v_s} \tag{2}
\]

The conditions that shearer and scraper conveyor running in same and opposite direction are shown in Figure 2 where shearer is simplified into particle. From the beginning of shearer coal cut to the start of scraper conveyor coal drop, it takes time \( t' = \frac{(L-x_0)}{v_c} \), and with the time \( t'' = \frac{(L+(v_c-v_s)t_1-x_0)}{v_c} \), the coal cutted off can be unloaded by scraper conveyor completely. Then, the real-time load of scraper conveyor can be calculated as below.

\[
Q = \begin{cases} 
q_s v_c t, & 0 \leq t < t_s \\
q_s v_c t - q_s v_s(t-t') & t_s \leq t < t' \\
q_s v_c t - q_s v_s(t-t'') & t' \leq t \leq t'' 
\end{cases} \tag{3}
\]

(2) When shearer working in tilted-cutting S-bend segment:

Unlike working in straight line segment, the cut depth of shearer drums is linear increase to the maximum \( S \) from shearer starting tilted-cutting till its back drum entering to straight line, shown as Figure 3.
Figure 3. Cut depth change of shearer working in tilted-cutting S-bend.

In the process, the cross section of coal loaded in scraper conveyor is increasing. Just idealize the coal loaded in scraper conveyor as tri-prism, then there is an equality relationship between the coal amount cut off in tilted-cutting segment by shearer and the amount loaded by scraper conveyor.

\[ \frac{1}{2} h S \gamma N = \frac{1}{2} (v_c - v_s) \frac{N}{v_c} A \gamma \]  

(5)

Thus, \( A = h S \gamma / (v_c - v_s) \) which shows the maximum coal cross section in scraper conveyor when tilted-cutting finished can be reasoned from equation (5). The unloading time of coal mined in tilted-cutting S-bend segment is:

\[ t_s = \frac{(v_c - v_s) N}{v_c} = \frac{(v_c - v_s) N}{v_c |v_c|} \]  

(6)

Thus, the cross section of coal unloaded at scraper conveyor nose side at a specific time can be calculated as:

\[ A' = \frac{t - t'}{t_s} A = \frac{(t - t') h S \gamma v_c^2}{N (v_c - v_s)^3} \]  

(7)

The amount of coal has been unloaded is:

\[ \frac{1}{2} v_c (t - t') \cdot A' \gamma = \frac{1}{2} v_c (t - t') \frac{(t - t') h S \gamma v_c^2}{N (v_c - v_s)^3} \gamma = \frac{(t - t')^2 h S \gamma v_c^2 v_s^2}{2 N (v_c - v_s)^3} \]  

(8)

The tilted-cutting process spend time \( t_s = N/v_c \). So the real-time amount of coal \( Q_s \) cut by shearer is:

\[ Q_s = \frac{1}{2} Sl h t \cdot A' \gamma = \frac{q v_c^2 t^2}{2N} \]  

(9)

Then, the real-time load of scraper conveyor in the process of tilted-cutting segment are expressed as equation (10) and (11). The situation that \( t_s \leq t' \) happens at tail side of scraper conveyor shown as:

\[ Q = \begin{cases} \frac{q v_c^2 t^2}{2N} & 0 \leq t < t_s \\ \frac{1}{2} q_s N & t_s \leq t < t' \\ \frac{1}{2} q_s N - \frac{(t - t')^2 q v_c^2 v_s^2}{2 N (v_c - v_s)^3} & t' \leq t \leq t'^* \end{cases} \]  

(10)

If \( t_s > t' \), mainly at the nose side of scraper conveyor, then:

\[ Q = \begin{cases} \frac{q v_c^2 t^2}{2N} & 0 \leq t \leq t' \\ \frac{q v_c^2 t^2}{2N} - \frac{(t - t')^2 q v_c^2 v_s^2}{2 N (v_c - v_s)^3} & t' \leq t < t_s \\ \frac{1}{2} q_s N - \frac{(t - t')^2 q v_c^2 v_s^2}{2 N (v_c - v_s)^3} & t_s \leq t \leq t'^* \end{cases} \]  

(11)

Therefore, the real-time load of scraper conveyor in a cycle cutting coal process is calculated and shown by Matlab in Figure 4 based on the parameters in Table 1 and the sequence listed in Table 2, while the speed of shearer and scraper conveyor remain constant as most traditional speed set mode.
Figure 4. Scraper conveyor loads in a cycle cutting coal process.

From Figure 4, we can get that when shearer working in straight line segment, the load of scraper conveyor will increase or decrease linearly in large variable range. Meanwhile, the coal accumulated or unloaded too fast at certain times will be bad for healthy and stable operation of scraper conveyor. Shearer in S-bend segment walks at a lower speed 2m/min confined to curved path and reverse in no time at endpoint, thus the load of scraper conveyor has fluctuation but light. Therefore, coordinated speed planning will mainly focus on shearer straight line working segment.

3. Coordinated Speed Planning Strategy of Scraper Conveyor and Shearer

3.1. Multi-objective optimization model

The aim of scraper conveyor and shearer coordinated speed planning is to ensure the load of scraper conveyor in reasonable range, so to realize continuous and efficient production. Meanwhile, considering mechanical life, the planning also need to avoid regulating speed frequently. Therefore, the substance of coordinated speed planning of scraper conveyor and shearer is turned out to be a multi-objective problem which should search the optimal solution in available speed range.

Generally, a given multi-objective problem with $m$ objective functions and $n$ decision variables can be described as below:

$$
\begin{align*}
\min \ y &= F(x) = (f_1(x), f_2(x), \cdots, f_m(x)) \\
\text{s. t.} : \ g_i(x) &\leq 0, \quad i = 1, 2, \cdots, q \\
&\quad h_j(x) = 0, \quad j = 1, 2, \cdots, p \\
x &= (x_1, x_2, \cdots, x_n) \in X \subseteq \mathbb{R}^n \\
y &= (y_1, y_2, \cdots, y_m) \in Y \subseteq \mathbb{R}^m
\end{align*}
$$

(12)

The linear weighted sum method distributing weights for each sub-objective function to convert multi-objective problem into single objective problem are expressed as follow. Where, $X_f$ is feasible solutions set in which $x$ satisfies all constrain conditions, $\omega_i$ is weights, usually adopting regularization method to make \( \sum_{i=1}^k \omega_i = 1 \).

$$
\begin{align*}
\min f(x) &= \sum_{i=1}^k \omega_i f_i(x) \\
\text{s. t.} : x \in X_f
\end{align*}
$$

(13)

3.2. Particle swarm optimization

For a given particle swarm, $\text{Swarm} = \{ x_1^{(k)}, x_2^{(k)}, \cdots, x_m^{(k)} \}$, $m$ stands for number of particles, $d$ denotes dimension of solving space. Position vector of $i$-th particle at $k$-th iteration in search space can be described by $x_i^{(k)} = (x_{i1}^{(k)}, x_{i2}^{(k)}, \cdots, x_{id}^{(k)})$, which may be a possible solution. In change process of particle position, personal best position corresponding to its best fitness is represented as $\text{Pbest}$, and $\text{Gbest}$
stands for global best position. Accordingly, velocity vector \( v_i^{(k)} = (v_{i1}^{(k)}, v_{i2}^{(k)}, \ldots, v_{id}^{(k)}) \) denotes particle movement in each dimension space [6].

Velocity and position renewal equations of particles respectively expressed as follows are the core of PSO. Where \( c_1 \) and \( c_2 \) are accelerating factors, \( r_1 \) and \( r_2 \) are random numbers in \([0, 1]\), and \( \omega \) is inertia weight.

\[
\begin{align*}
    v_{id}^{(k+1)} &= \omega \cdot v_{id}^{(k)} + c_1 \cdot r_1 \cdot (p_{id}^{(k)} - x_{id}^{(k)}) + c_2 \cdot r_2 \cdot (p_{gd}^{(k)} - x_{id}^{(k)}) \\
    x_{id}^{(k+1)} &= x_{id}^{(k)} + v_{id}^{(k+1)}
\end{align*}
\]  

(14)

The basic flow of PSO for solving optimization problem can be presented as follow:

Step 1: Randomly initialize the particles including the search position and velocity. Define all PSO algorithm parameters, such as inertia weight \( \omega \), accelerating factors \( c_1, c_2 \), swarm size \( m \), maximum iteration \( k_{max} \), etc.

Step 2: Calculate the fitness value of each particle using the evaluation function. In this paper, the evaluation function will be defined by equation (15) as follow in Section 3.3.

Step 3: Update the Pbest particles by comparing the fitness value with the experience of each individual. The best evaluation value among all Pbest is the Gbest.

Step 4: Modify the velocity and position of each particle according to equations (14).

Step 5: If the number of iterations reaches \( k_{max} \), then stop. The latest Gbest is the optimal solution. Otherwise go back to step 2.

3.3. The proposed method

After establishing the problem model and analyzing PSO algorithm, the scraper conveyor and shearer coordinated speed planning process based on multi-objective PSO is prepared as follows.

(1) Objective function. The objective function aggregated by three sub-objectives with positive coefficients is constructed as follows:

\[
F = \omega_1 \cdot f_{\text{stability}} + \omega_2 \cdot f_{s\_\text{range}} + \omega_3 \cdot f_{c\_\text{range}}
\]  

(15)

Where, \( f_{\text{stability}} = \frac{1}{n} \sum_{i=1}^{n} (Q_i - \bar{Q})^2 \) is variance of scraper conveyor loads to estimate the primary goal about load stationarity. The volatility of shearer haulage speed and scraper conveyor speed are denoted by \( f_{s\_\text{range}} = \frac{1}{m} \sum_{i=1}^{m} (v_{i} - \bar{v})^2 \) and \( f_{c\_\text{range}} = \frac{1}{k} \sum_{i=1}^{k} (v_{i} - \bar{v})^2 \) respectively. Distribute weights for three sub-objective functions with experience \( \omega_1=0.7, \omega_2=0.15, \omega_3=0.15 \).

(2) Particle encoding. Represent particle in two-dimensional matrix as \( \mathbf{D} \times \mathbf{M} \) to suit the two principals speed planning problem as the encoding example in Table 3. Where, \( \mathbf{M} \) columns represent the speed adjustment times, \( \mathbf{D} \) rows imply that a particle has \( \mathbf{D} \)-dimensional attributes, \( \mathbf{D}=3 \) in this article, meanwhile \( \mathbf{D}_1 \) stands for shearer haulage speed, \( \mathbf{D}_2 \) donates scraper conveyor speed, and \( \mathbf{D}_3 \) is the duration of each matching shearer haulage speed and scraper conveyor speed.

Table 3. Particle encoding example.

| M1  | M2  | M3  | M4  | M5  |
|-----|-----|-----|-----|-----|
| D1  | v_{i1} | v_{i2} | v_{i3} | v_{i4} | v_{i5} |
| D2  | v_{i1} | v_{i2} | v_{i3} | v_{i4} | v_{i5} |
| D3  | t_{i1} | t_{i2} | t_{i3} | t_{i4} | t_{i5} |

(3) Constraints.

1) Shearer haulage speed range \( g_1 : v_{s_{\text{min}}} < |v_s| < v_{s_{\text{max}}} \). Where, \( v_{s_{\text{max}}} \) is the maximum design haulage speed of shearer, \( v_{s_{\text{min}}} \) is minimum speed ensuring productivity relating to condition of working face.

2) Scraper conveyor speed range \( g_2 : v_{c_{\text{min}}} < v_c \leq v_{c_{\text{max}}} \). Similarly, adopt rated chain speed and minimum speed ensuring productivity to restrain scraper conveyor chain speed.

3) Duration of shearer each constant haulage speed \( g_3 : t_{i} \geq t_{i_{\text{min}}} \). The constraint is created depending on the purpose to limit speed volatility of shearer and scraper conveyor.
4) Equality constraint about the studied working face section and the particles: \[ h_i \leq \sum_{u=1}^{n} v_{iu} t_{iu} \leq L. \]

Where, \( L \) is the length of working face section given coordinated speed planning. The equality constraint reveals that after several speed modulations, the travelled distance of shearer happens to be the length of studied working face section.

(4) Compute of fitness. The fitness is value of objective function, where \( f_{s \_range} \) and \( f_{c \_range} \) can be easily calculated by particle information, but \( f_{\text{stability}} \) relies on scraper conveyor loads analysis in Section 2. And it is worth pointing out that the mining process would be divided into different stages according to speed adjustment moment of shearer and scraper conveyors. Though different mining stages are consecutive, next mining stage is to start when the last one didn’t finish unloading. Therefore, the loads superposition between each stage should be considered. Based on above analysis, compute process of fitness which will be called in the proposed speed planning method is programmed.

The complete flowchart of the coordinated speed planning strategy based on PSO is presented in Figure 5.

4. Simulation Example and Application Experiment

4.1. Simulation example

The shearer and scraper conveyor coordinated speed based on proposed method are planned adopting parameters in Table 1. While shearer and scraper conveyor running in same direction, the Gbest particle with fitness \( F=8.57 \) below indicating that speed should be accommodated four times. Scraper conveyor load curve acquired from the particle and PSO convergence curve are presented in Figure 6(a).
Similarly, the Gbest particle with fitness $F=12.24$ for shearer and scraper conveyor running in opposite direction is shown as below. Speed adjusting number is three, and relevant curves are expressed in Figure 6(b).

![Graphs showing planning results for different running directions.](image)

From Figure 6, the load curves of scraper conveyor no longer linearly rise then fall as shown in Figure 4, but change gradually within small range in majority of the working time on account of several mining stages combination. Besides, working as planned speed will not impair efficiency for the unobvious working time change compared with usual constant speed working mode.

| Working mode | Maximum change rate | Load average | Load variance |
|--------------|---------------------|--------------|---------------|
| Same direction | Constant speed | 26.58 t/min | 8.80 t | 24.89 t² |
| | Planned speed | 8.91 t/min | 8.61 t | 10.25 t² |
| Opposite direction | Constant speed | 10.95 t/min | 10.04 t | 23.05 t² |
| | Planned speed | 7.80 t/min | 9.68 t | 14.01 t² |

From Table 4, it can be observed that the scraper conveyor load average and volatility evaluated by variance have declined markedly according to the proposed method. Meanwhile, the apparent declined maximum change rate of load curve indicates that the problem of coal accumulated or unloaded too fast in short time can be improved.

4.2. Application experiment

In this section, an online system based on the proposed method had been developed and applied in ground simulated fully-mechanized face in Zhangjiakou, China as shown in Figure 7, which can simulate actual automatic working state of outfits in working face.
Figure 7. The experimental site and its hardware construction and communication.

The experiment is performed in working face range from 20m to 70m, and operating parameters are set in coordinated speed monitoring platform based on WinCC configuration software. Taking shearer and scraper conveyor operation in same direction as example, call PSO coordinated speed planning module to plan their speed in target working scope. The planned speed will be send to onboard PLC controllers for tracking. Then collect running data including the two real time speeds and the scraper conveyor current reflecting load change and return to WinCC platform. The result of coordinated speed planning and tracking experiment is shown Figure 8.

Figure 8. Coordinated speed planning and tracking experiment interface.

Further, a compared experiment that shearer and scraper conveyor working in usual constant speed was carried out to verify the strategy with the same working face range from 20m to 70m. Archive load current and compare with the one collected in planned speed tracking test, and the result is presented as follow in Figure 9.
Figure 9. Comparison of scraper conveyor load current in different working modes.

Statistics based on scraper conveyor load current data indicates that mean in PSO coordinated speed planning and tracking mode is 24.15A lower than 28.04A in usual constant speed working mode, thus application of the proposed method can reduce overall system energy consumption while maintaining mining efficiency. More importantly, the variance of load current correlated with planned speed working mode is 16.52 which decreases by 61.3% clearly than variance 42.68 in constant speed running mode, so the method turns out to be effective in enhancing scraper conveyor load stability and reliability.

5. Conclusion
An integrated coordinated speed planning strategy of scraper conveyor and shearer based on scraper conveyor loads analysis is proposed to prevent large load fluctuation of scraper conveyor for fear of frequent breakdowns as heavy loads or several bad working conditions. Scraper conveyor loads analysis model on the basis of shearer bidirectional mining technology is established. The proposed method is constructed reasonably by the combination of the loads analysis and multi-objective PSO algorithm. Moreover, simulation example and application experiment are carried out to validate the proposed method. The results show that scraper conveyor load fluctuation are much smaller than traditional solution.

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