Research on the Four-stage Drill Pipe Automatic Conveying System

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Abstract. The four-stage drill pipe automatic conveying system is developed to solve the problem that the capacity of the existed drill pipe conveying system is very limited, which needs workers to add drill pipes frequently during drilling and can’t fit the development of the automatic rig. The four-stage drill pipe conveying path plan of the multidirectional automatic rig is designed based on the general conveying path and the starting point normalization, and operating mechanisms are designed, including the pipe box, the transferring device, the main and the deputy mechanical arm. This plan is helpful to reduce the height of the rig by using the room below the side of the pipe box. According to the mechanism, the conveying path is adjusted adaptively to avoid interference between the conveying system and the rig. It is verified by the theoretical calculation and the model machine test that pipes can be delivered automatically and accurately by the four-stage automatic conveying system.

Keywords: Four-stage conveying system; Automatic rig; Drill pipe conveying; Conveying path; Mechanical arm; Top-opened pipe box.

1. Introduction

The traditional way to load and unload drill pipes for the coal mine rig depends on manpower, in which the labour intensity is high, the efficiency is low and there is a big safety hidden danger (Lyu, & Xin, 2019). In recent years, with the development of the research and application of the automatic rig, automatic drill pipe conveying system, as an important supporting device, is constantly innovating. In the field of intelligent rock drilling trolley and mine core rig, the automatic drill pipe conveying system appears firstly. They are used to convey small pipes and don’t have a mechanical arm (Abuah, Okenyi, Erhunmwansee, Onafeso, & Abdallah, 2020; Bakulin, Aldawood, Silvestrov, Hemyari, & Poletto, 2020; Belousov, & Grigorev, 2020), so they are not suitable to the coal mine automatic rig. The most common types of the existing automatic drill pipe conveying system used in coal mine rigs are the open-framed type with a mechanical arm and the rotary type with a simple conveyer (Pu, 2018) which only have a small capacity. They requires manual addition of pipes several times during the drilling process, becoming the barrier of the further improvement of the automatic coal mine rig.

In order to solve the above problems, the four-stage drill pipe automatic conveying system is developed based on the analysis, planning and decomposition of the conveying path, which realises the large capacity and the accurate transmission of drill pipes.
2. Planning for Conveying Path

2.1. Path Planning for a Single Drill Pipe

According to the working characteristics of the automatic coal mine rig, the conveying path of the drill pipe path starts at a specific position in the pipe box, and ends when the axis of the pipe coincides with the drilling axis between the power head and the gripper.

Due to the uniformity of the material and the symmetry of the structure, the gravity center of the pipe is taken as the origin of both the starting and the ending coordinate system. So the gravity center at the starting point is defined as the origin of the reference coordinate system (RCS), the drilling direction along the axis of the pipe as $+x$, the vertical direction to the rig as $+y$ and the vertical upward as $+z$.

For convenience, the reference coordinate system $Oxyz$ is set coincident with the starting coordinate system (SCS) $O_{SCS}xyz$. Similarly, the gravity center at the ending point is defined as the origin of the ending coordinate system (ECS) $O_{ECS}xyz$, $+x_E$ goes in the same direction as $+x$, $+z_E$ in the same as $+z$ and $+y_E$ in the opposite of $+y$. Conveying the pipe from the pipe box is the position transformation from the origin of SCS to that of ECS, which is completed in RCS.

To ensure the generality of the path planning, the three components of the origin of SCS $O_{SCS}(x_{SO}, y_{SO}, z_{SO})$ and that of ECS $O_{ECS}(x_{EO}, y_{EO}, z_{EO})$ are all different in the RCS (Guo, Shuang, & Kan, 2019; Wang, Li, Ge, & Cao, 2018; Wu, Yue, Wei, & Liu, 2018; Xiao, Shen, & Ni, 2018; Yang, Zhang, Qin, Guo, & Wang, 2018). The coordinate systems and the general conveying path are shown in figure 1. The power head is the rotating power output unit, the frame is the feeding output unit and the gripper is the pipe-holding unit.

![Figure 1. General conveying path of a single drill pipe.](image1)

The conveying path vector is:

$$\mathbf{r}_{SE} = (x_{EO}, y_{EO}, z_{EO}) - (x_{SO}, y_{SO}, z_{SO})$$

(1)

2.2. Starting Point Normalization

Starting point normalization is the step to make every pipe to start conveying at the same point. The way to place pipes is designed as the form of multi-column and multi-layer, shown in figure 2.

![Figure 2. Starting point normalization.](image2)

Pipes are arranged in a rectangle with $n$ rows and $m$ layers (rows). Using the principle of matrix, the nearest column to the frame is defined as column 1 and the top layer as row 1. The pipe in this position is $g^{(1,1)}$, of which the starting point is $O_{SCS}^{(1,1)}(x_{SO}^{(1,1)}, y_{SO}^{(1,1)}, z_{SO}^{(1,1)})$. The rest of pipes are numbered similarly. Obviously, all pipes will pass through $g^{(1,1)}$ on the way to the drilling axis, so the origin of SCS of $g^{(1,1)}$ is taken as the starting point for all pipes. In comparison with the transmission of $g^{(1,1)}$, ...
other pipes firstly need a normalization of their RCSs to point $O_{S}^{(1,1)}$. The path vector of a random pipe $g^{(p,q)}$ to $g^{(1,1)}$ is:

$$\mathbf{r}_{(1,1)}^{(p,q)} = (x_{SO}^{(p,q)}, y_{SO}^{(p,q)}, z_{SO}^{(p,q)}) - (x_{SO}^{(1,1)}, y_{SO}^{(1,1)}, z_{SO}^{(1,1)})$$

where, $p$ is the column code, $1 \leq p \leq n$; $q$ is the row code, $1 \leq q \leq m$.

2.3. Design of the Four-stage Path Plan

The four-stage path plan can be decomposed into four stages including starting point normalization, descent, alignment and translation, shown in figure 3:

- Normalization: the starting point of pipe $g^{(p,q)}$ is moved to $O_{S}^{(1,1)}$, including subpath B1 and B2.
- Descent: $g^{(p,q)}$ is moved to the bottom of the right side of the pipe box through B3.
- Alignment: $g^{(p,q)}$ can be respectively aligned with the drilling axis in the direction of axis $x$ and $z$, through B4 and B5.
- Translation: through B6, $g^{(p,q)}$ is moved along axis $y$ to the drilling axis.

The movement along axis $x$ is operated at the bottom of the right side of the pipe box through a descent and a lift (B3 and B5) which are helpful to reduce the heights both of the conveying system.

3. Structural Design of the Conveying System

3.1. Overall Design Plan

According to the four-stage path plan, the overall plan of the conveying system is designed as follows:

- The pipe box is relatively fixed to the main rig.
- Subpath B1-B3 is operated by the same mechanism and B1 and B2 by one sliding pair.
- B4 is operated by another sliding pair.
- B5 and B6 are operated by two different sliding pairs of one mechanism which can also adjusting the dip angle following the frame.

The four-stage automatic conveying system is composed of a pipe box, a carrier, a main arm and an assistant arm, shown in figure 4.
3.2. Pipe Box

The pipe box is shown in figure 5. Its main frame is a vertical multi-column and top-opened box. The capacity can be adjusted by changing the columns or height according to requirement, although the pipe box of the model rig is designed to have 9 columns and 8 rows, which can contain 72 pipes in total.

![Figure 5. Structure of the pipe box.](image)

3.3. Assistant Arm

The assistant arm, shown in figure 6, is composed of the claw, the first and the second telescopic joint, the translational joint and so on. The claw is a clamp to hold the pipe driven by a cylinder. The translation joint, which takes the pipe move along axis $y$ to realize subpath $B_2$, is a gear and rack mechanism driven by a motor. The first and the second telescopic joint are both a sliding pair driven by a cylinder, combining to realize subpath $B_1$ and $B_3$.

![Figure 6. Structure of the assistant arm.](image)

3.4. Carrier

The carrier, shown in figure 7, is composed of the box frame, the adjuster, the adjusting cylinder, the track and so on. The box frame—container of pipes moves along axis $x$ driven by the adjusting cylinder which makes the carrier or pipes to align with the drilling axis to realize subpath $B_4$. The adjuster, driven by another cylinder, makes the width adjustable to improve the aligning accuracy.
3.5. Main Arm
The main arm, shown in figure 8, is composed of the incline joint, the turning joint, the telescopic joint and the claw. The incline joint has a rotary reducer which has a dip angle range from -90° to +90° to make the pipe to stay at the same dip angle with the frame. The turning joint has a rotating shaft driven directly by a motor, moves the pipe along axis $z$ to accomplish subpath $B_5$ and the transition to $B_6$ in the meantime. The main advantage of it is to reuse the space above the carrier to reduce the dimension of the rig. The claw and the telescopic joint have the similar functions and structures with those of the assistant arm. The subpath $B_6$ is accomplished by the telescopic joint.

4. Theoretical Checking and Model Machine Tests
4.1. Differences between the Actual Path and the Plan
Compared with the above plan, the subpath T1—T4 of the actual conveying path, shown in figure 9, is the same with B1—B4. But for reasons of the overall arrangement and the interference avoidance, there are some differences between the actual conveying path and the plan:
- The actual starting point $O_{S}^{(1,1)}$ is above $g^{(1,1)}$ rather than on it when normalization.
- The movement along axis $z$ is operated by the rotating supath $T_5$, and the transition to $T_6$ can be completed in the meantime.

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Figure 7. Structure of the carrier.

Figure 8. Structure of the main arm.

Figure 9. Actual conveying path.
4.2. Theoretical Checking for the Starting and the Ending Point

Pipe $g^{(9,8)}$, the farthest one from the drilling axis, is taken as the example for the checking calculation. According to the dimensions of the 3D model of the rig, the coordinates of the starting and the ending point are:

\[
\begin{align*}
(x_{SO}^{(9,8)}, y_{SO}^{(9,8)}, z_{SO}^{(9,8)}) &= (0, -824, -677.5) \\
(x_{EO}^{(9,8)}, y_{EO}^{(9,8)}, z_{EO}^{(9,8)}) &= (576, 1336, -68)
\end{align*}
\]  

(3)

Operations and parameters related with the path in the pipe conveying process are listed in Table 1.

**Table 1.** Operations and parameters in the pipe conveying process.

| Mechanism    | Operation   | Direction | Value/mm | Variable | Path |
|--------------|-------------|-----------|----------|----------|------|
| Assistant arm| Stretching out | $-z$    | /        | /        | $T_1$|
|              | Retraction  | $+z$     | 677.5    | $z_1$    |      |
|              | Translation | $+y$     | 1056     | $y_1$    | $T_2$|
|              | Stretching out | $-z$   | 274.5    | $z_2$    | $T_3$|
| Carrier      | Translation | $+x$     | 576      | $x_1$    | $T_4$|
| Main arm     | Grabbing    | /        | /        | /        |      |
| Dip angle adjusting | /     | /        | /        | /        | $T_5$|
| Turning      | $+y$        | 781      | $y_2$    |          |      |
| Stretching out | $+z$    | 206.5    | $z_3$    |          |      |
|              | $+y$        | 323      | $y_3$    |          | $T_6$|

Adding the parameters in Table 1 to the coordinates of the starting point, the coordinates of the ending point are:

\[
\begin{align*}
  x_{SO}^{(9,8)} &= x_{SO}^{(9,8)} + x_1 = 576 \\
  y_{SO}^{(9,8)} &= y_{SO}^{(9,8)} + y_1 + y_2 + y_3 = 1336 \\
  z_{SO}^{(9,8)} &= z_{SO}^{(9,8)} + z_1 + z_2 + z_3 = -68
\end{align*}
\]  

(4)

where, parameters in the positive direction are defined as positive values, negative values otherwise. Comparing equation (3) and (4), it is clear that the planned starting and ending point separately coincide with the measured ones on the 3D model.

4.3. Model Machine Tests

According to the above plan, a ZYWL-4000Y multidirectional automatic rig with a four-stage automatic conveying system is manufactured and tested, shown in Figure 10. The conveying path matches well with the plan and the mechanisms act to the scheduled positions and have no interference.

**Figure 10.** Model machine tests.

5. Applications

Tingnan Coal Mine in Shanxi has used ZYWL-4000Y automatic rig with the four-stage automatic conveying system to drill gas drainage holes since October 2019. Comparing with traditional rigs, the number of workers is reduced from 3 to 1, the drilling efficiency is increase from nearly 2800
m/month to 3400 m/month, promoted more than 20%, and the working safety is greatly improved without frequent pipe feed during the drilling process.

6. Conclusion
(1) The paths of all pipes are designed uniformly by using the principle of matrix to generalize the convey path, which is helpful to simplify the conveying path plan and the mechanisms.
(2) The carrier, which takes pipes moving along axis $x$, is set below the side of the pipe box, so the heights of the conveying system and the rig can be reduced.
(3) According to the corresponding relationship between the path and the kinematic pairs, the automatic conveying system and its main parts are designed. The path is adjusted based on the actual structure to fit the overall arrangement and to avoid interference.
(4) It is proved by the model machine tests and application that the conveying path of the four-stage automatic conveying system is simple and reasonable, mechanisms operate accurately and reliably and the automatic transmission is efficient and safe.
(5) According to the applications, the structural strength of the assistant arm needs to be enhanced.

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