Research on Walking Wheel Slippage Control of Live Inspection Robot

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Abstract. To solve the problem of walking wheel slippage of a live inspection robot during walking or climbing, this paper analyzes the climbing capacity of the robot with a statics method, designs a pressing wheel mechanism, and presents a method of indirectly identifying walking wheel slippage by reading speed of the pressing wheel due to the fact that the linear speed of the pressing wheel and the walking wheel at the contract point is the same; and finds that the slippage state can not be controlled through accurate mathematical models after identifying the slippage state, whereas slippage can be controlled with fuzzy control. The experiment results indicate that due to design of the pressing wheel mechanism, friction force of the walking wheel is increased, and the climbing capability of the robot is improved. Within the range of climbing capability of the robot, gradient is the key factor that has influence on slippage of robot, and slippage can be effectively eliminated through the fuzzy control method proposed in this paper.

1. Introduction

The track path of the live inspection robot is 110-220kV overhead high voltage lines [1-3]. The robot passed through 330kV power frequency withstand test in high voltage hall of Wuhan University, each index response and loaded devices of the robot operate normally, and the control system is immune to interference of high electric field. In practice of actual line, walking wheel slippage accelerates abrasion of walking wheel, reduces repairing efficiency, and causes energy load to the live inspection robot with limited power capacity [4-6]. In the meanwhile, slippage may cause positioning error for robots using encoder or millemeter for positioning. Thus, slippage identifying and controlling of walking wheels will be focus of research on control of live inspection robot walking along transmission lines.

2. Research on slippage control of live inspection robot

The robot is prone to slippage due to the line structure characteristics and erection environment such as small cross section of lines, sag caused by gravity of the line itself and height difference between adjacent towers, thus reducing the working efficiency of the robot and increasing energy consumption of the robot. With deepening of research and application of live inspection robot, it turns to be an important part of live inspection robot research to increase its self-adaption climbing capacity and repair working efficiency.

References [7-8] analyzed slippage of spherical robots, established a dynamic mode during robot climbing, and presented corresponding control methods which however, are difficult to apply to
suspension moving robots. References [9-10] studied slippage of lunar rovers, established a slippage mode that wheels of the lunar rover interact with the ground. In the meanwhile, a slippage rate formula was present with the gradient of the ground taken into account. In addition, an anti-slip model is established and simulation of the model is carried out, but analysis and simulation in this method were only in theory.

The reference [11] analyzed the climbing capacity of the live inspection robot, divided the walking states of the robot on overhead ground wires into constant speed, deceleration, acceleration and stop, and then adjusted structure of the robot according to different states so as to increase adaptability of the live inspection robot to gradient.

In conclusion, so far, only a few researches on slippage of wheel type moving robots have been done at home and abroad, and there is hardly any research on slippage of live inspection robots at present. The robot works in an environment with rigid-flexible coupling characteristics and force loading conditions of the walking wheel are very complex, thus it is very difficult to identify slippage with a dynamic method. Therefore, this paper is intended to present a new method for identifying and controlling slippage of walking wheel of the live inspection robot so as to increase working efficiency of the live inspection robot and avoid severe abrasion of the walking wheel.

3. Analysis of climbing capacity and slippage of robot

3.1. Analysis of climbing capacity of robot

When the robot slips, the common cause lie in large gradient, thus it is necessary to study the maximum climbing capacity of the robot at first.

![Figure 1. Static model of robot walking.](image1)

![Figure 2. Schematic diagram of robot skid identification.](image2)

The prototype of the robot is shown in figure 9. The robot is of a double-arm antisymmetric suspension structure, thus force bearing state of only one arm is analyzed herein. The statics model of the robot walking along the ground wire at certain gradient is shown in figure 1, where in I is the walking wheel of the robot, II is the pressing wheel, III is the control cabinet of the robot, α is gradient, and G is gravity of the robot. In order to improve the climbing capability of the robot, a pressing wheel mechanism is designed on the arm to increase positive pressure loaded on the walking wheel to increase friction force.

The statics equation when the robot climbs a gradient is shown in formula (1).

\[ f - G_x \geq 0 \]  

\( G_x \) is component is the robot’s gravity along the x direction shown in figure 1, which is described in the following formula.
\[
G_x = -\frac{1}{2} G \cos(\alpha)
\]  

(2)

In figure 1, support force by lines along the y direction consists of two parts: reaction support force \( F_N \) of lines to the robot after the robot’s own gravity is applied to the lines and pressing force \( F_k \) that the pressing wheel transmits to the walking wheel.

\[
f = -\mu(F_N + F_k)
\]  

(3)

\[
F_k = kx
\]  

(4)

In formula (3), \( \mu \) is the friction coefficient between the walking wheel of the robot and the ground wire. In formula (4), \( k \) is the elastic coefficient of a pressing spring on the pressing wheel. Only one arm is in analysis, thus the support force is only set to be half of the total support force.

\[
F_N = \frac{1}{2} G \cos \alpha
\]  

(5)

The maximum transformation of the spring is \( x_m \), and in the formula, \( x \in (0, x_m) \). By integrating formula (1), (2), (3), (4) and (5) simultaneously, a formula can be obtained as follows.

\[
\sin(\alpha - \arctan(\mu)) \leq \frac{2\mu k x}{G\sqrt{1+\mu^2}}
\]  

(6)

According to formula (6), without taking the driving capacity of the walking wheel into consideration, positive pressure applied by the pressing wheel is the most important factor influencing climbing capacity of the robot. With the maximum transformation of the pressing spring \( x_m \) taken into account, the maximum climbing angle of the robot is that

\[
\alpha_{\text{max}} = \arcsin\left(\frac{2\mu k x_m}{G\sqrt{1+\mu^2}}\right) + \arctan(\mu)
\]  

(7)

When the pressing wheel does not apply any pressure, suppose the maximum climbing angle of the robot is \( \alpha_{\text{min}} \), then it can be obtained from formula (7) that

\[
\alpha_{\text{min}} = \arctan(\mu)
\]  

(8)

In accordance with formula (7), in theory, when the robot rolls on a line with the gradient smaller than \( \alpha_{\text{max}} \), slippage of the robot can be totally prevented. Thus, it is necessary to find a slippage identifying method first to judge the state of the robot and then control the slippage.

### 3.2. Analysis of robot slippage

According to analysis of the climbing capacity of the robot, the pressing force \( F_k \) is very important for increasing the gradient adaptability of the robot. It can be seen from formula (7) that when \( F_k = 0 \), namely the pressing wheel does not apply any pressure, the maximum climbing angle of the robot is \( \arctan(\mu) \), and the pressing pressure can bring out extra \( \arcsin\left(\frac{2\mu k x}{G\sqrt{1+\mu^2}}\right) \) climbing angle increment for the robot.

When slippage of the robot is controlled, as in formula (7), it only requires to measure the friction coefficient \( \mu \) between the walking wheel of the robot and the ground wire, the elastic coefficient \( k \).
of the pressing spring, and the gravity $G$ of the robot itself. Then the stroke of the pressing spring can be controlled according to gradient of the lines $\alpha$.

4. Slippage identifying

4.1. Slippage identifying model
When slippage of the robot is controlled, the walking state of the robot is as shown in figure 2. The pressing wheel is not provided with a drive unit, belonging to a driven mechanism. When the walking wheel of the robot does not slip, the walking wheel and the pressing wheel rotate synchronously, and their walking distance in a certain period of time is the same, thus the linear speed $v_1$ of the walking wheel is the same with the linear speed $v_2$ of the pressing wheel, namely $v_1 = v_2$. $v_1 = \omega_1 r_1$ and $v_2 = \omega_2 r_2$, wherein $\omega_1$ is the angular speed of the walking wheel, $r_1$ is the radius of the walking wheel, $\omega_2$ is the actual angular speed of the pressing wheel, and $r_2$ is the radius of the pressing wheel. When the robot does not slip, suppose the non-slip angular speed of the pressing wheel is $\omega_{2m}$, the following formula needs to be met.

$$\omega_1 r_1 = \omega_{2m} r_2$$ (9)

4.2. Slippage identifying method
The angular speed of the walking wheel, $\omega_1$, can be directly read through the driver, and the actual angular speed of the pressing wheel, $\omega_2$ can be acquired by a slippage sensor installed in the pressing wheel. Within a period of time $\Delta t$ when the pressing wheel rotates, the slippage sensor acquires a certain number of pulse signals, and the pulse signals are counted by a counter arranged on a multifunctional data acquisition card. Thus, actual angular speed of the pressing wheel, $\omega_2$, is described in the following formula.

$$\omega_2 = \frac{2\pi N}{n\Delta t}$$ (10)

In this formula, $\Delta t$ is acquisition time interval, $N$ is the number of pulse acquired by the counter within the time interval $\Delta t$, $n$ is the number of pulse per revolution of the pressing wheel.

Therefore, the slippage state of the robot can be defined through $\omega_2$, the actual angular speed of the pressing wheel.
1) $\omega_2 = 0$, the robot slips totally.
2) $0 < \omega_2 < \omega_{2m}$, the robot does not slip at all.
3) $\omega_2 = \omega_{2m}$, the robot does not slip.

5. Slippage control method
When the walking wheel slips, according to formula (7), the slippage can be eliminated by controlling the pressing force $F_k$ on the pressing wheel. The degree of slippage of the walking wheel directly defines magnitude of pressing force applied to the pressing wheel, and the concept of slippage extent is introduced to quantize the degree of slippage of the robot.

Slippage degree: the ratio of $\omega_2$, the actual angular speed of the pressing wheel to $\omega_{2m}$, the non-slip angular speed of the pressing wheel is defined as slippage degree. The slippage degree is represented by $\varepsilon$, and its mathematical expression is as follows.
Slippage degree reflects the degree of slippage of the walking wheel, and its domain is $\varepsilon \in [0,1]$, the smaller $\varepsilon$ is, the higher the degree of slippage is. $\varepsilon_m = 1$ is set as the target slippage degree, representing that the robot does not slip.

By means of the analysis of slippage degree hereinbefore, it can be known that when the slippage degree of the robot returns to $\varepsilon = \varepsilon_m$ from different slippage degrees, the required pressing force applied by the pressing wheel will surely be different. In order to better describe the robot’s returning to the slippage $\varepsilon = \varepsilon_m$ from any original state, the concept of slippage increment is introduced.

**Slippage increment**: suppose the slippage degree of the walking wheel of the robot at the time $t_1$ is $\varepsilon$, the bearing pressing force is $F_1$, after the pressing wheel applies or releases certain pressure $\Delta F$, the slippage degree of the robot reaches $\varepsilon_m$ at the time of $t_2$, and the beating pressing force is $F_2$, and then the slippage increment within the period of time $\Delta t$ is denoted by $\Delta \varepsilon$, and its mathematical expression is as follows.

$$\Delta F = F_2 - F_1 = k\Delta \varepsilon \quad (12)$$

In this formula, $k$ stands for the elastic coefficient of the pressing spring, and $\Delta \varepsilon$ stands for slippage increment. When $\Delta F$ is a negative value, it represents that the pressing force of the pressing wheel at previous time is too large and the pressing wheel needs to release a pressing force with the magnitude of $\Delta F$. Correspondingly, when $\Delta F$ is a positive value, it represents that pressing force of the pressing wheel at previous time is too small and the pressing wheel needs to apply a pressing force with the magnitude of $\Delta F$. The domain is $\Delta \varepsilon \in [-\varepsilon_m, \varepsilon_m]$, when $\Delta \varepsilon = 0$, it presents that the robot does not slip at the previous time.

5.1. **Relation between slippage increment and slippage degree**

According to the analysis above, in case of the fixed line gradient, the smaller the slippage degree is, the larger the required slippage increment is. The direct control means of slippage of the robot, as shown in formula (12), slippage can be controlled by using the pressing wheel to compress the pressing spring upwards or releasing the pressing spring downwards.

When the line gradient is 12 degrees and the spring is of different original deformations, different slippage degrees of the robot can be controlled by applying different slippage increments. Variations are as shown in figure 3, when $y_1, y_2$ and $y_3$ are the required slippage increments for adjusting the robot under different slippage degrees into the non-slip state when the original deformations of the spring are $\Delta x_s = 0 mm$, $\Delta x_s = 0 mm$ and $\Delta x_s = 40 mm$ respectively. As shown in figure 3, the lower the slippage degree is, the larger the slippage increment is.

5.2. **Relation between slippage increment and gradient**

Under the same slippage degree, the larger the gradient is, the larger the slippage increment is. This kind of qualitative relationship lies between the pressing force increment required for controlling slippage and gradient. Carry out experiments with the robot under different gradients, adjust the original pressing force to enable the walking wheel to keep the same slippage degree $\varepsilon$, and then supplement pressing force to control the robot not to slip. According to recorded experimental data, the relation between pressing force increment and gradient is as shown in figure 4, $G_1$ stands for variation of the slippage increment $\Delta \varepsilon$ of the robot with gradient when the slippage degree of the robot...
meets $\varepsilon = 0$; $g_2$ stands for variation of the slippage increment $\Delta x$ of the robot with gradient when the slippage degree of the robot meets $\varepsilon = 0.3$; and $g_3$ stands for variation of the slippage increment $\Delta x$ of the robot with gradient when the slippage degree of the robot meets $\varepsilon = 0.8$.

Figure 3. Relationship between skid increment and degree of slip.

Figure 4. Relationship between skid increment and gradient.

5.3. Design of slippage controller

According to the analysis of causes of slippage of the robot described above, slippage of the robot is related to line gradient $\alpha$, the friction coefficient between the walking wheel and the ground wire as well as the slippage degree $\varepsilon$. During actual operation of the robot, reasons of slippage of the robot are more complicated, material of the ground wire, rust degree of the surface, rain, snow or dust covered on the surface and the speed state of the robot can all affect the slippage state of the robot. Even when the robot walks on line of the same type, the slippage conditions are different when the robot is on different line sections. In addition, the surface of the walking wheel is in continuous abrasion so that roughness of the surface of the wheel groove of the walking wheel changes all the time, thus it is very difficult to determine the friction coefficient between the walking wheel and the surface of the line. Slippage can not be effectively controlled by adjusting the pressing force with accurate mathematical models, thus the fuzzy control method can be used to solve this problem effectively.

Figure 5 shows the slippage fuzzy controller designed by this paper, and the controller comprises two inputs and one output. The line gradient $\alpha$ and the slippage degree $\varepsilon$ are used as the inputs of the system respectively, and then close loop of the line gradient is realized through the inclination angle sensor, and the close loop of slippage degree is achieved through the slippage sensor. The output is pressing force increment $\Delta x$, and $T_d$ is external disturbance.

Figure 5. Sliding fuzzy controller.
5.3.1. Determination of domain of discourse and membership function. The input variable slippage degree is acquired by the slippage sensor. As shown in formula (11), the range of slippage degree of the robot is $\varepsilon \in [0,1]$. Thus, the domain of discourse of $\varepsilon$ is $[0,1]$ in 6 grades, with the gap between each two adjacent grades of 0.17. The linguistic variable is divided into 7 levels, which comprises, from small to large based on slippage degree, very small (NK3), small (NK2), relatively small (NK1), medium (K0), relatively large (PK1), large (PK2) and very large (PK3). Each fuzzy partition membership function $\mu$ is expressed in a triangular function as shown in Figure 6.

The input variable line gradient is acquired by the inclination angle sensor. The climbing capacity of the live inspection robot adopting a roll running manner is 30 degrees. Thus, the domain of discourse of $\alpha$ is $[0,30]$ in 6 grades, with the gap between each two adjacent grades of 5 degrees. The linguistic variable is divided into 7 levels, which comprises, from small to large in accordance with gradient, very small (NS3), small (NS2), relatively small (NS1), medium (S0), relatively large (PS1), large (PS2) and very large (PS3). Each fuzzy partition membership function $\mu$ is expressed in a triangular function as shown in Figure 7.

The output of the fuzzy controller is the stroke of a pressing motor of the pressing wheel and slippage increment. The stroke reflects magnitude of pressing force increment, its domain of discourse is $[0,360]$ in mm, and can be read through a driver. The domain of discourse of slippage increment is divided into 6 grades with the gap between each two adjacent grades of 60mm, and is divided into into 7 levels in a fuzzy partition mode, with corresponding linguistic variables being extremely small (DN3), very small (DN2), relative small (DN1), medium (D0), relatively large (PD1), very large (PD2) and extremely large (PD3). Its fuzzy partition membership function $\mu$ is expressed in a triangular function as shown in Figure 8.

5.3.2. Fuzzy slippage control rules. Fuzzy control rules need to be established in the fuzzy control process, which are established based on knowledge and practical experience of human. The fuzzy control rules are presented as a group of fuzzy conditional statements, such as “if-then” statements. For the slippage fuzzy controller, its form of rules are as follows.

$$R_1: \text{If } \varepsilon \text{ is } A_1 \text{ and } \alpha \text{ is } B_1, \text{then } I \text{ is } C_1$$

$$R_2: \text{If } \varepsilon \text{ is } A_2 \text{ and } \alpha \text{ is } B_2, \text{then } I \text{ is } C_2$$

$$\ldots$$

$$R_n: \text{If } \varepsilon \text{ is } A_n \text{ and } \alpha \text{ is } B_n, \text{then } I \text{ is } C_n$$

The fuzzy relation corresponding to the general control rule of the fuzzy controller is $R$, and
\[ R = R_1 \cup \ldots \cup R_n \] \hspace{1cm} (13)

\[ R_i = (A_i \text{and} B_i) \rightarrow C_i \] \hspace{1cm} (14)

Suppose the input fuzzy quantity of the fuzzy controller is that \( e \) is \( A' \) and \( \alpha \) is \( B' \), then through Mamdani approximate reasoning with the fuzzy control rules, it can be obtained that the output fuzzy quantity \( I \) (represented by fuzzy geometry \( C' \))is that

\[ C' = (A' \text{and} B')R \] \hspace{1cm} (15)

The judgment rule is as shown in table 1. In the process of slippage control, the fuzzy control plan is adjusted according to experimental experience, when the gradient \( \alpha \) is small, the slippage degree will not bring about medium (K0), relatively large (PK1), large (PK2) and very large (PK3).

| Rank | NK3 | NK2 | NK1 | K0 | PK1 | PK2 | PK3 |
|------|-----|-----|-----|----|-----|-----|-----|
| NS3  | PD1 | D0  | ND1 | ND2| ND2 | ND2 | ND3 |
| NS2  | PD1 | PD1 | ND1 | ND1| ND2 | ND2 | ND3 |
| NS1  | PD2 | PD1 | D0  | ND1| ND2 | ND2 | ND3 |
| S0   | PD2 | PD1 | D0  | D0 | ND1 | ND2 | ND3 |
| PS1  | PD3 | PD2 | PD1 | D0 | ND1 | ND2 | ND3 |
| PS2  | PD3 | PD3 | PD1 | D0 | ND1 | ND1 | ND3 |
| PS3  | PD3 | PD3 | PD2 | D0 | ND1 | ND1 | ND3 |

6. Test research and analysis

The experimental line is as shown in figure 9. The line gradient range is \([10^\circ, 30^\circ]\), and the gradient can be adjusted according to different test objectives. The rope in figure 9 is used for protect safety of the robot, applying no towing force to the robot.

On a simulated line, the speed is set as 3km/h, and the fuzzy control method is used to carry out climbing slippage tests when the robot is on the line with gradients of 10 degrees, 20 degrees and 30 degrees respectively. The time response curves of slippage control are shown in figure 10, figure 11 and figure 12 respectively. According to figure 10, the robot only slips at the startup stage, and then quickly returns to the normal walking state because a gap is reserved between the pressing wheel of the robot and the ground wire, and the linear speed of the walking wheel is not consistent with that of the pressing wheel from time to time. After the gradient comes up to 20°, figure 11 shows that slippage of the robot aggravates, resulting from the fact that component of the gravity of the robot itself along the direction perpendicular to the line decreases, and support force of the robot is reduced, consequently the pressing wheel needs to supplement support force so as to increase friction force in the walking direction. Compared with figure 10, the robot spends 5 seconds to adjust itself to the normal walking state. Figure 12 shows that the slippage degree of the robot in the adjustment process repeats, this is mainly due to the fact that at large gradient, the two walking wheels are not in the same straight line because of gaps between the two arms of the robot and the guide rail. Thus in the adjustment process, when gaps are caused between the pressing wheel and the ground wire, slippage will be aggravated. However, after the pressing wheel continuously applies pressing force to the ground wire, influence of the gaps is eliminated, and slippage will disappear.
As known from the analysis of test results described above, gradient is the dominant factor having influence on slippage of the robot, while the fuzzy control method presented in this paper can effectively eliminate slippage, and validity of control method is verified.

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure10.png}
\caption{Time response curve of gradient degree of 10 degree slip.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure11.png}
\caption{Time response curve of gradient degree of 20 degree slip.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure12.png}
\caption{Time response curve of gradient degree of 30 degree slip.}
\end{figure}

7. Conclusion
This paper analyzed the material cause of slippage of the robot at first, pointed out that gradient is the dominant factor having influence on normal walking of the robot, then analyzed the climbing capacity of the robot and presented the maximum climbing angle of the robot, and obtained the theoretical basis for why the pressing wheel can effectively increase the climbing capacity of the robot. On this basis, the paper developed the slippage control method, used the method of controlling the stroke of the pressing wheel to control slippage of the robot, and analyzed the relation between slippage increment and slippage degree and relation between slippage increment and gradient. To solve the problem that accurate mathematical models can not be established for slippage, this paper designed a fuzzy controller using slippage degree and gradient as input and slippage increment as output. Finally, tests are carried out for the proposed slippage control method. The test results show that the presented fuzzy slippage control method is correct, and can effectively eliminate slippage of the robot and meet application requirements.

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