1. Introduction

High-voltage transmission lines have an important impact on the development and stability operation of the power industry, which need regular maintenance so as to ensure the stability of overhead high-voltage transmission lines. Che et al. and Aracil et al. [1, 2] give the structure of the multisplit transmission lines and through the data from grid companies indicate that the multisplit transmission lines are the main channel to undertake the power transmission; the most typical representative of this kind line is the double-split conductor. Singh et al. and Park et al. [3, 4] give the structure and characteristic of the single-split transmission lines. Compared with the single-split transmission line, the multisplit power transmission line has stronger power transmission capability. Chithamacharyulu et al. [5] give the structure and function of the spacer bar, and it is an important line fitting on double-split conductors; the main purpose is to restrict the relative motion between the subconductors and to maintain the geometric shape of the double-split conductors under normal operation. At present, the double-split conductors can be adopted by 220 KV and 330 KV transmission lines; all these can be shown in references [6, 7]. In order to ensure the distance between the double-split conductors remains unchanged so as to meet the electrical performance and reduce the surface potential gradient; in the case of short circuit, no electromagnetic force can be generated between the split wires, resulting in mutual attraction collision or even instantaneous
attraction collision, but after the accident has been eliminated, the split wires can return to the normal state. Therefore, Pouliot et al. and Wang et al. [8, 9] show that the spacer bar is installed at a certain distance between the gears, which can restrain not only the gears vibration but also the breeze vibration. However, Ngo et al., Sun et al., Lu et al., and Li et al. [10–13], respectively, proposed the factors such as breeze, ice, rain, and snow can cause the displacement and corrosion of spacer bars. Therefore, regular inspection and maintenance of spacer bars are necessary. The main way to deal with this problem is to climb up the tower and transmission line with operation tools and reset or replace the spacer bars. This kind method requires power cutting operation, which is inefficient and cannot guarantee personal safety. Compared with single-split transmission lines, double-split transmission lines have stronger power transmission capability and wider application. With its operation environment being heterogeneous, which has been elaborated in reference [14], and more complex, it puts forward higher requirements for the operation. Another important way is to use the power cable robot as Xu et al. [15] describe. At present, many different power cable robots, such as reference [16], proposed an insulator replacement robot, which is a wheel-arm compound robot walking on power transmission line and can complete replacement of insulators online. Jiang et al. [17] proposed a damper replacement robot, which can service at 220 kV high-voltage line. Jiang et al. [18] proposed a basic configuration of drainage plate tightening robot and developed a physical prototype. Wang et al. [9] proposed a wire repair robot which can realize the function of wire repair. Most of these robots only face single-split conductors and cannot accommodate multisplit conductor operation. Based on the abovementioned analysis, this paper developed a four-wheel-driven spacer bar maintenance robot for double-split transmission lines, as shown in references [19, 20], and proposed a motion planning and control method for disassembly and installation of spacer bars; a virtual robot prototype has been designed; the simulation results show that the developed robot system meets the requirements of the workspace and the force control between the robot and the operation object in the operation process. The research studies have important theoretical significance and practical application value to improve power system automation.

2. Operation Environment and Objects

Analysis of Double-Split Transmission Lines

Regarding the double-split transmission lines, each conductor has two phases, which act as a conductor erection method and adopted through UHV (Ultrahigh Voltage) transmission lines to suppress corona discharge and reduce line reactance. Each phase conductor consists of several small diameter branch conductors, and each branch conductor is spaced at a certain distance and arranged in a symmetrical polygon. The spacer bar can be installed between two-phase conductors and distributed even on the double-split conductors between towers. Compared with the single-split conductor, double-split conductor has stronger power transmission capability and is much more representative in high-voltage transmission lines. The typical structure and spacer bar distribution of double-split transmission lines is shown in Figure 1.

The spacer bar is installed between double-split transmission lines. Because of the natural environment and other factors, there will be some typical malfunction problems, such as clamp pull-out, baseball support head pull-out, rivet grinding, and breaking. Figures 2(a)–2(d) show the basic structure of the spacer bar. A complete spacer bar consists of two clamp bodies which are connected by the connection rods. The connection rod and the clamp body are also distributed with spherical hinges. The open of the clamp body is sleeved on the transmission line and fixed on the double-split transmission line through tightening the spacer bar bolts.

3. Mechanism Design of the Mobile Robot

Through the analysis of operation principle and operation object, the DOF (Degree of freedom) number the robot required, the manipulator, and their corresponding functions can be obtained, as shown in Table 1. In order to adapt to the high-voltage double-split transmission lines environment, the robot mobile platform adopts four-wheel-driven mode, four mobile arms are equipped with walking wheels, and the walking wheel walks on the double-split transmission line. The mobile robot body is equipped with a mobile sliding platform, and the double manipulator is installed on the sliding platform. The manipulator 1 is a 2-DOF mechanism, which can horizontally move in the working space between double-split transmission lines. The manipulator is brought to the working space through the stretch mechanism with the spacer bar supporting mechanism. Then, through the rotation mechanism, the spacer bar rotates slowly and the clamp bayonet of the spacer bars is fitted with the double-split conductor. At this time, the bolt tightening mechanism is carried by manipulator 2 through the vertical and horizontal joints so as to bring the bolt tightening mechanism into the working space and align the bolts on the double spacer bar clamps which have been inserted into the conductors, respectively. The spacer bar is fixed on the double-split conductor by bolt tightening operation, thus completing the installation operation of the spacer bar on the double-split conductor. The robot operation manipulator is mounted on the robot arm; the manipulator 1 is composed by clamping mechanism and supporting mechanism; the function of the clamping mechanism is to let the spacer bar naturally fall on the supporting mechanism after loosening the spacer bar bolt by the tightening mechanism, and the spacer bar is clamped to prevent it from falling. The configuration diagram of the double-split transmission line spacer bar replacement robot is shown in Figure 3.
4. Robot Kinematics-Dynamics Analysis and Operation Motion Planning

4.1. D-H Kinematics Modeling. At present, Lai et al. and Vijay and Jena [21, 22] detailed and introduced the D-H coordinate method; it is generally used to describe the relative relationship of rods in kinematics analysis for robot manipulators. The basic coordinate system of the mobile platform and the linkage coordinate system of the operation arm can be established, respectively. Taking a connection rod $i + 1$ as an example, the inherent attributes of connection rod $i + 1$ can be determined by the length of the connection rod and the twist angle of the connection rod. The spatial position of the connection rod $i + 1$ can be determined by its relative position with the adjacent connection rod $i$, which can be determined by the offset of the connection rod and the rotation angle of the connection rod. Therefore, the connection rod can be described through a $4 \times 4$ matrix, which is composed of four parameters in the last connection rod coordinate system. Through the superposition of the homogeneous transformation matrix, the position and attitude matrix of the connection rod with operation manipulator in base coordinates can be obtained, and the position and attitude matrix of the operation manipulator can be obtained by translation. Regarding the robot in this paper, the mechanical arm 1 has two joints and mechanical arm 2 has three joints; according to the sequence of series connection, the first vertical joint, the first rotation joint, the second stretch joint, the second horizontal joint, and the second vertical joint of the robot manipulator are, respectively, used. According to the D-H method, the coordinate system {0}–{5} can be established, as shown in Figure 4. Wherein, the base coordinate system {0} is established at the coincidence of the mobile platform and the initial position of the operation arm 1. Connection rod coordinate systems {1}, {2}, {3}, {4}, and {5} can be established on each joint of the double manipulators, and their D-H parameters can be shown in Table 2.

According to the theoretical derivation of the connection rod parameters and joint variables, the equation expression of the position and attitude matrix $^{i-1}T_i$ of the connection rod $i$ coordinate system in the connection rod $i-1$ coordinate system can be obtained as equation (1). Through substituting the parameters and variables of the connection rod in Table 1 into equation (2), the position and attitude matrix of the connection rod coordinate system {i} in the coordinate system {i–1} can be obtained. Suppose the width of double-split conductors is $l$, through the kinematics analysis, the coordinate transformation can be obtained as matrix equations (2)–(4), and the operation manipulator coordinate relative to the base coordinate equation (5) can be obtained. Therefore, the forward kinematics solution can be obtained as equation (6), wherein $p_x$, $p_y$, and $p_z$ are the position coordinates of the robot manipulator end in the space coordinate system, $o_x$, $o_y$, and $o_z$ are the posture coordinates of the robot manipulator end in the space coordinate system:

$$
^{i-1}T_i = \begin{bmatrix}
\cos \theta_i & -\sin \theta_i & 0 & a_{i-1} \\
\sin \theta_i \cos \alpha_{i-1} & \cos \theta_i \cos \alpha_{i-1} & -\sin \alpha_{i-1} & -d_i \sin \alpha_{i-1} \\
\sin \theta_i \sin \alpha_{i-1} & \cos \theta_i \sin \alpha_{i-1} & \cos \alpha_{i-1} & d_i \cos \alpha_{i-1} \\
0 & 0 & 0 & 1
\end{bmatrix},
$$

(1)

$$
^0T_i = \text{Trans}(0,0,d_i) = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 658 + d_i \\
0 & 0 & 0 & 1
\end{bmatrix},
$$

(2)
\[
1_2 T = \text{Trans}(d_x, d_y, 0) = \begin{bmatrix}
1 & 0 & 0 & \frac{l}{2} \sin \theta \\
0 & 1 & 0 & \frac{l}{2} \cos \theta \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix},
\]

\[
2_3 T = \text{Rot}(z, \theta_i) = \begin{bmatrix}
\cos \theta & -\sin \theta & 0 & \frac{l}{2} \sin \theta_i \\
\sin \theta & \cos \theta & 0 & \frac{l}{2} \cos \theta_i - 1 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix},
\]

\[
T_3 = 0_1 T_2 1_2 T_3 = \text{Trans}(0, 0, d_1) \times \text{Trans}(d_x, d_y, 0) \times \text{Rot}(z, \theta_i)
\]

\[
T_3 = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 658 + d_1 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 & \frac{l}{2} \sin \theta \\
0 & 1 & 0 & \frac{l}{2} \cos \theta \\
0 & 0 & 1 & \sin \theta_i \cos \theta_i - 1 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\cos \theta & -\sin \theta & 0 & \frac{l^2}{4} \sin \theta \sin \theta_i \\
\sin \theta & \cos \theta & 0 & \frac{l^2}{4} \cos \theta_i (\cos \theta_i - 1) \\
0 & 0 & 1 & 658 + d_1 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
\begin{cases}
p_x = \frac{l^2}{4} \sin \theta \sin \theta_i, \\
p_y = \frac{l^2}{4} \cos \theta_i (\cos \theta_i - 1), \\
P_z = 658 + d_1,
\end{cases}
\]

\[
\begin{cases}
x = \cos \theta, \\
y = \sin \theta, \\
z = 0,
\end{cases}
\]

\[
0_x = -\sin \theta, \\
0_y = \cos \theta, \\
0_z = 0.
\]

4.2. Robot Dynamics Modeling. Taking the mobile operation robot operation arm 1 as an example, the derivation of robot dynamics equations can be obtained through using the Lagrange method which are shown as follows. Both links are symmetrical, with the mass center at the center of the link, the length are \(l_1\) and \(l_2\), the mass are \(m_1\) and \(m_2\), moment of inertia is \(I_1\), the distance from the center of the stretch joint to the center of rotation joint is \(d_2\), the effective moment of inertia at joint \(i\) is \(I_{ii}\), and the moment at joint \(i\) is \(I_{ii}\); the inertia matrix obtained from the link position parameter of the operation arm 1 is as follows:

\[
\begin{bmatrix}
I_{xx1} & 0 & 0 \\
0 & I_{yy1} & i \\
0 & 0 & I_{zz1}
\end{bmatrix},
\]

\[
\begin{bmatrix}
I_{xx2} & 0 & 0 \\
0 & I_{yy2} & i \\
0 & 0 & I_{zz2}
\end{bmatrix}
\]

The total kinetic energy of the robot system is as follows:
The total potential energy of the robot system is as follows:

\[ K = K_1 + K_2, \]
\[ K_1 = \frac{1}{2} m_1 l_1^2 \ddot{\theta}_1^2 + l_{yy1} \dot{\theta}_1^2, \]
\[ K_2 = \frac{1}{2} m_2 \left( d_1^2 \ddot{\theta}_1^2 + d_2^2 \right) + l_{yy2} \dot{\theta}_1^2, \]
\[ K = \frac{1}{2} \dot{\theta}_1^2 \left( m_1 l_1^2 + I_{yy1} + I_{yy2} + m_2 d_2^2 \right) + \frac{1}{2} m_2 d_2^2. \]

The total potential energy of the robot system is as follows:

\[ L = K - P, \]
\[ = \frac{1}{2} \dot{\theta}_1^2 \left( m_1 l_1^2 + I_{yy1} + I_{yy2} + m_2 d_2^2 \right) + \frac{1}{2} m_2 d_2^2 - g s_1 \left( m_1 l_1 + m_2 d_2 \right). \]
Figure 3: Configuration of the double-split transmission line spacer bar replacement robot.

Figure 4: Continued.
Table 2: Connection rod parameters and joint variables of the robot manipulator.

| Rod number $i$ | Rod length $a_{i-1}$ (mm) | Twist angle $\alpha_{i-1}$ (°) | Bias $d_i$ (mm) | Joint angle $\theta_i$ (°) | Joint variable range |
|----------------|-----------------------------|--------------------------------|----------------|---------------------------|---------------------|
| 1              | 658                         | 0                              | Stretch $d_1$ | 0                         | 5~217 mm            |
| 2              | 250                         | 90                             | 0             | Rotation $\theta$         | 0~90°               |
| 3              | 690                         | 0                              | Stretch $d_2$ | 0                         | 5~298 mm            |
| 4              | 468                         | 0                              | Vertical $d_3$| 0                         | -234~234 mm         |
| 5              | 400                         | 0                              | Horizontal $d_4$| 0                        | -275~5 mm           |

Figure 4: Connection rod coordinate system of the robot manipulator. (a) Coordination system establishment. (b) D-H coordinate system.

Figure 5: The motion planning of the spacer bar replacement robot.
Through the partial derivative of function (10) and bring it into equation (9), we can obtain the Lagrange dynamic equation:

\[
\begin{align*}
\frac{\partial E}{\partial \dot{q}} & = \left[ (m_1 I_1 + I_{yy1} + I_{yy2} + m_2 d_2^2) \dot{\theta}_1 \right]_1 \\
\frac{\partial E}{\partial \dot{q}} & = \left[ 0 \right]_2 \\
\frac{\partial E}{\partial \dot{q}} & = \left[ gc_1 (m_1 l_1 + m_2 d_2) \right]_3 \\
T & = (m_1 I_1 + I_{yy1} + I_{yy2} + m_2 d_2^2) \dot{\theta}_1 + 2m_2 d_2 \dot{\theta}_1 d_2 + gc_1 (m_1 l_1 + m_2 d_2), \\
F & = m_2 \ddot{d}_2 - m_2 d_2 \dot{\theta}_1^2 + m_2 g s_1.
\end{align*}
\]

(11)

Rewrite equation (11) in closed form as equation (12), so as to obtain the robot dynamics model as equation (13):

\[
\begin{bmatrix}
T \\
F
\end{bmatrix}
= \begin{bmatrix}
(m_1 I_1 + I_{yy1} + I_{yy2} + m_2 d_2^2) \dot{\theta}_1 + 2m_2 d_2 \dot{\theta}_1 d_2 + gc_1 (m_1 l_1 + m_2 d_2) \\

m_2 \ddot{d}_2 - m_2 d_2 \dot{\theta}_1^2 + m_2 g s_1
\end{bmatrix},
\]

(12)

\[
T = D(q) \ddot{q} + H(q, \dot{q}) + G(q), \\
D(q) = \begin{bmatrix}
(m_1 I_1 + I_{yy1} + I_{yy2} + m_2 d_2^2) & 0 \\
0 & m_2
\end{bmatrix}, \\
H(q, \dot{q}) = \begin{bmatrix}
2m_2 \ddot{d}_2 \dot{\theta}_1 d_2 \\
-m_2 \ddot{\theta}_1^2
\end{bmatrix}, \\
G(q) = \begin{bmatrix}
gc_1 (m_1 l_1 + m_2 d_2) \\
m_2 g s_1
\end{bmatrix}.
\]

(13)

4.3. Operation Motion Planning. The two-dimensional and three-dimensional motion planning of the robot double-split spacer bar replacement operation are shown in Figures 5 and 6, respectively. The main process of robot spacer bar maintenance includes the disassembly of the old spacer bar and the installation of the new spacer bar. In the process of disassembly of the old spacer bar, the robot is first hoisted onto the HVTL (High-Voltage Transmission Line) manually, the rotation joint rotates the operation arm 1 to the working state, and the robot walks along the wire to the working posture. Operation arm 1 moves to the working position through the stretch joint, and the gripper of the motor-driven clamping mechanism shrinks and clamps the old spacer bar connection rod. The operation arm 2 moves to the working position through the stretch joint and the horizontal joint, aligning the bolt tightening mechanism with the bolt at one end of the old spacer bar, the bolt tightening mechanism loosens the old spacer bar bolt. The vertical joint aligns the bolt tightening mechanism with the bolt at the other old spacer bar, and the bolt tightening mechanism loosens the bolt at the other old spacer bar. Operation arm 1 removes the old spacer bar from the HVTL by rotation joints and stretch joints. When the operation has been finished, the double operation arm withdraws from the working posture and the spacer bar maintenance robot goes off line.

The installation process of new spacer bars is as follows; firstly, the robot with the new spacer bar is hoisted on the line manually. The rotation joint rotates the operation arm 1 to the working state, and the robot walks along the HVTL to the working posture. The operation arm 1 moves to the working posture through the stretch joint so that the spacer bar and the transmission line are equal in height. The rotation joint places the new spacer bar on the HVTL so that the new spacer bar clamp holds the HVTL. The operation arm 2 moves to the working space through the stretch joint and the horizontal joint and aligns the bolt tightening mechanism with the bolt at one end of the new spacer bar.
Tightening the bolt at one end of the new spacer bar by the bolt tightening mechanism, the vertical joint aligns the bolt tightening mechanism with the bolt at the other end of the new spacer bar, and the bolt tightening mechanism tightens the bolt at the other end of the new spacer bar, and the bolt tightening sleeve aligns and locates the connection bolts at the two ends of the spacer bar, respectively. The spacer bar clamp is abstracted as an ideal particle; the kinematics analysis of the dual manipulator shows that the position and posture of the spacer bar clamp and the sleeve of manipulator 2 are relative to the joint variables \((\theta_1, \theta_2, \theta_3, \theta_4, \theta_5)\) for the dual manipulator in the basic coordinate system; the real-time position and posture of the spacer bar clamp and the double mechanical sleeve can be obtained when the joints move. After the robot is on line, the walking wheels move slowly along the transmission line and locate the spacer bar to realize the operation object initial posture, and the attitude is defined as the initial position of the dual manipulators. In this state, the two clamps of the spacer bar on manipulator 1 can be abstracted as ideal particle A and B, the installation points of the spacer bar on wire are \(P_1\) and \(P_2\), and the bolt tightening sleeve on manipulator 2 is C. The control goal is to approximate point A and point B to point \(P_1\) and point \(P_2\), respectively, and point C to point \(P_1\) and point \(P_2\), respectively, and all these can be seen in Figure 4(a). The coordinate of the manipulator in the basic coordinate system is \(P_{0i}(x_{0i}, y_{0i}, z_{0i})\). The coordinate of the dual clamps on the double-split wire can be defined as the ideal posture of the dual manipulators. In this state, the coordinate of the manipulator in the basic coordinate system is \(P_{ri}(x_{ri}, y_{ri}, z_{ri})\). After the walking wheel locates the spacer bar, the robot enters the initial working position and can reach the working space through the coordinated motion of each joint of the dual manipulators. Therefore, the control goal of spacer bar replacement operation is to control the manipulator arm by dynamically selecting the motion parameters of robot’s each joint so that it can continuously approach its ideal position from the initial position and attitude. The mathematical description of the posture error and the approximation target is shown in equation (14)–(16):

\[
\begin{align*}
e(\theta_1, \theta_2) &= P_1' - P_{1i}, \\
e(\theta_3, \theta_4, \theta_5) &= P_2' - P_{2i}, \\
\lim_{P_{01} \to P_{1i}} \left\| e(\theta_1, \theta_2) \right\| &= 0, \\
\lim_{P_{02} \to P_{2i}} \left\| e(\theta_3, \theta_4, \theta_5) \right\| &= 0, \\
\lim_{P_{0i} \to P_{ri}} \left\| e(\theta_1, \theta_2, \theta_3, \theta_4, \theta_5) \right\| &= 0.
\end{align*}
\]

4.4. Analysis of Key Technologies in Operation Process. According to the robot operation motion planning, the key technical problems in the operation process mainly include two aspects. The first operation arm 1 clamps the spacer bar clamp on the HVTL through the stretch joint and the rotation joint, and the second operation arm 2 bolt tightening sleeve aligns and locates the connection bolts at the two ends of the spacer bar, respectively. The spacer bar clamp is abstracted as an ideal particle; the kinematics analysis of the dual manipulator shows that the position and posture of the spacer bar clamp and the sleeve of manipulator 2 are relative to the joint variables \((\theta_1, \theta_2, \theta_3, \theta_4, \theta_5)\) for the dual manipulator in the basic coordinate system; the real-time position and posture of the spacer bar clamp and the double mechanical sleeve can be obtained when the joints move. After the robot is on line, the walking wheels move slowly along the transmission line and locate the spacer bar to realize the operation object initial posture, and the attitude is defined as the initial position of the dual manipulators. In this state, the two clamps of the spacer bar on manipulator 1 can be abstracted as ideal particle A and B, the installation points of the spacer bar on wire are \(P_1\) and \(P_2\), and the bolt tightening sleeve on manipulator 2 is C. The control goal is to approximate point A and point B to point \(P_1\) and point \(P_2\), respectively, and point C to point \(P_1\) and point \(P_2\), respectively, and all these can be seen in Figure 4(a). The coordinate of the manipulator in the basic coordinate system is \(P_{0i}(x_{0i}, y_{0i}, z_{0i})\). The coordinate of the dual clamps on the double-split wire can be defined as the ideal posture of the dual manipulators. In this state, the coordinate of the manipulator in the basic coordinate system is \(P_{ri}(x_{ri}, y_{ri}, z_{ri})\). After the walking wheel locates the spacer bar, the robot enters the initial working position and can reach the working space through the coordinated motion of each joint of the dual manipulators. Therefore, the control goal of spacer bar replacement operation is to control the manipulator arm by dynamically selecting the motion parameters of robot’s each joint so that it can continuously approach its ideal position from the initial position and attitude. The mathematical description of the posture error and the approximation target is shown in equation (14)–(16):
4.5. BP NN-Based Robot Motion Control System. Because the control deviation is realized by the feedback of the closed-loop system, we choose the most commonly used inverse error neural network at present, namely, BP NN. The architecture of the BP network-based robot motion control system for the robot is shown in Figure 7. The input of the controller is motion posture error, the output is the control variable $u(t)$, and the motion control instruction can be produced under the common effects of a flexible working environment, error compensation, and a remote commander. Here, the remote commander, which has the highest priority, is used to ensure the safety of the operation and is ready to control the motor brake at any time. The speed of each joint motor of the mechanical arms can be adjusted through BP NN dynamic learning. Then, the actual posture can be obtained by integral transformation. By comparison with the desired posture, the posture error can be obtained and taken as the input to the controller, thus forming a closed-loop control system. Through dynamic adjustment of the controller, when the posture error approaches 0, the dynamic adjustment process will be finished and the double manipulators can be aligned with the key spot in the spacer bar replacement operation process.

5. Robot Principle Prototype Development and System Simulation Analysis

5.1. Robot Virtual Prototype and Principle Mobile Platform Design Development. Through the integration of the designed chassis, operation arm, and operation manipulator, a virtual prototype model of the live-working robot for replacing double-split transmission line spacer bars can be formed in the INVENTOR development environment, which is a new tool to analyze the robot structure system design elaborated in reference [23, 24] and shown in Figure 8(a). Through the integration of the electrical system, mechanical system, and software system, the principle mobile platform can be formed, as shown in Figures 8(b) and 8(c).

Through the relevant tests and experiments on the robot mobile platform, we can obtain the relevant physical characteristics of the robot mobile platform, as shown in Table 3.

5.2. Simulation Analysis of Robot Kinematics System. In order to verify the robot motion performance, the robot kinematics simulation parameters have been performed so as to solve the kinematics simulation after adding the kinematics pairs and drivers among the robot manipulator joints in the ADAMS environment; in the preprocess module, the motion curves of each joint in the simulation process can be drawn, as shown in Figure 9, and the corresponding joint motion performance parameters are shown in Table 4.

The simulation results show that, in Figure 9(a), the displacement curve of the horizontal joint (red solid line) varies in a cubic function path within 0–5 s, and the process of beginning and end changes smoothly. The blue dotted line is the velocity curve which increases gradually from zero to maximum and then decreases gradually to zero according to the quadratic function. The rose dotted line is the acceleration curve which mutates from zero instantaneous to 18 mm/s² at the beginning movement, and from 18 mm/s² to zero at 2.5 s, the mutation range is within the acceptable range. Secondly, the displacement curve (red solid line) of the stretch joint is shown in Figure 9(b); it extends smoothly to the set position in 5–10 s according to the cubic function path and then remains stationary. Then, in Figure 9(c), the red solid line is an angle curve of rotation joint which changes smoothly within 10–15 s until the center of the end sleeve aligns with the operation object. In the last 5 s, the red solid line in Figure 9(d) is the vertical joint path curve which changes smoothly within 15–20 s. Therefore, in conclusion, according to the analysis criteria judgment of working space and joint moment of the robot mechanical system, the simulation results show that the ADAMS simulation model and the constraints model are all correct, and the robot motion parameters and the force characteristic meet the robot joints motion performance needs. The operation motion for the robot manipulator joint meets the kinematics requirements in the process of replacement of the spacer bar.

5.3. Simulation Analysis of Robot Dynamics System. Robots dynamic simulation is used to study the force constraints between the operation manipulator and the operation object in the operation process. Based on the dynamics analysis in Section 4.2, in order to verify the robot dynamic performance, the robot manipulator model can be established in ADAMS; save the robot 3D model as a copy in STEP format, which can be imported into the ADAMS environment, as shown in Figure 10. There is friction between the parts during the movement of each joint; therefore, the maximum static friction coefficient can be set as 0.1 and the dynamic friction coefficient can be set as 0.05. The conventional and inertial characteristics of each component are shown in Table 5. After the simulation operation, in each process module, the displacement and rotation angle corresponding to each connection rod joint, the joint force and moment, and the curve of the driving force and moment varying with time can be measured. The dynamic characteristics of horizontal, stretch, vertical, and rotational joints can also be obtained, as shown in Figure 11, and the corresponding joint force performance parameters are shown in Table 6. The judgment criteria for the effectiveness of simulation experiments are as follows: (1) the joint position range and joint force changes obtained through simulation are consistent with the robot’s operating motion process; (2) the results obtained from kinematics simulation can meet the requirements of the working space, that is, the end of the robot is in simulation and under the action of the obtained joint variables, the working object can be reached, and there is no working blind zone; (3) the results of the dynamic simulation can meet the force requirements of the working process, that is, in the replacement of the spacer bar, especially the end can be loosened or tightened the spacer bar bolt.
The simulation results show that, as shown in Figure 11(a), within 0–5 s, horizontal joint movement, others remaining stationary, the force on the horizontal joint is about 40.735 N. Within 5–10 seconds, stretch joint movement, the acceleration in the vertical direction increases suddenly and then decreases linearly to produce the same inertial force, and the press force applied on the horizontal joint increases suddenly and then decreases linearly. It is the same in 10 s–15 s and 15 s–20 s, up to 20 s; the joint of the manipulator stopped moving and the horizontal joint force is restored to 41 N compared with the initial state. As shown in Figure 11(b), the moving direction of the stretch joint is vertical, and the joint force is in the horizontal plane perpendicular to the vertical direction. Within 0–5 seconds, the horizontal joint moves at variable speed in the horizontal plane. The varying joint forces on the stretch joint.

**Table 3: Physical characteristics of the mobile platform.**

| Characteristics content | Test result |
|------------------------|-------------|
| Adapt wire             | LGJ240–LGJ400 |
| Power frequency withstand voltage | ≥330 kV |
| Weight                 | 40 kg |
| Robot mobile platform  | 3.8 kg |
| Spacer bar bolt tightening end | 40 kg |
| Shape size             | 800 * 300 * 200 mm |
| Driving speed          |             |
| Rolling rated speed    | 0.85 km/h  |
| MAX speed              | 4 km/h     |
| Robot camera           |             |
| Resolution             | 628 * 582  |
| Image format           | JPEG       |
| Communication distance | 1.5 km     |
| Anti-interference ability | OK         |
Figure 9: Continued.
cause the extensor to move horizontally with the horizontal joint. Within 5–10 s, the stretch joint moves vertically upward and the force of the stretch joint is the pressure between the inside arm and the outside arm, which is a constant value. Within 10 s–15 s and 15 s–20 s, other joint movements have a coupling effect on the stretch joint, which results in the change of joint force in accordance with the corresponding joint acceleration. Up to 20 s, the manipulator joints stopped moving, and the stretch joint returned to its initial state. As shown in Figure 11(c), within 0–10 seconds, the rotation joint remains in its initial state. Within 10 s–15 s, rotation joint movement, up to 15 s, the rotation joint stopped moving. Within 15 s–20 s, vertical joint movement, the gravity center change of the vertical move component cause the change of the joint force. As shown in Figure 11(d), within 0–10 s, because the gravity at the

Table 4: Joint motion performance parameters of robot different joint.

| Joint      | 0–5 s | 5 s–10 s | 10 s–15 s | 15 s–20 s |
|------------|-------|----------|-----------|-----------|
| Horizontal | ↑     | ↑↓↑↓     | 80 mm     | 0 0 80 mm | 0 0 0 0 |
| Stretch    | 0 0   | 0 0       | 30 mm     | 0 0 30 mm | 0 0 0 0 |
| Rotation   | 0 0   | 0 0       | 0 0       | 0 0       | 0 0 0 0 |
| Vertical   | 0 0   | 0 0       | 0 0       | 0 0       | 0 0 0 0 |

Note: ↑ means increasing; ↓ means decreasing; D means displacement; V means velocity; A means acceleration.

Table 5: Dynamic simulation parameters.

| Component      | Slide | Vertical | Rotation joint | Stretch joint |
|----------------|-------|----------|----------------|---------------|
| Mass (kg)      | 5.099 | 0.816    | 0.285          | 0.687         |
| I1 (kg mm²)    | 117263.177 | 2363.387 | 989.172        | 358.315       |
| I2 (kg mm²)    | 97541.557  | 2304.278  | 33.535         | 1265.322      |
| I3 (kg mm²)    | 21884.414  | 379.681   | 1003.778       | 1100.918      |
| Ixx (kg mm²)   | 308261.338 | 3296.324  | 3367.470       | 1224.726      |
| Iyy (kg mm²)   | 103905.157 | 2817.078  | 123.949        | 4868.605      |
| Izz (kg mm²)   | 212859.000 | 1697.411  | 3420.067       | 4333.886      |

Figure 9: Robot joint kinematic curve of the operation manipulator. (a) Horizontal joint. (b) Stretch joint. (c) Rotation joint. (d) Vertical joint.

Figure 10: Robot 3D model in ADAMS.
Figure 11: Continued.
operation manipulator is perpendicular to the direction of the vertical joint, there is a component which makes the vertical joint produce joint force. Within 10 s–15 s, rotation joint rotates, the angle between the vertical component and the vertical direction increases, and the component of the manipulator gravity acting on the vertical joint increases as a trigonometric function. Up to 15 s, the rotation joint stops rotation. Then, within 15 s–20 s, the vertical joint force remains constant. Therefore, according to the actual driving force of robot’s each joint obtained from the above-mentioned simulation results, the designed robot can meet dynamic performance, and the maximum driving force need to drive each moving pair. Then, the output torque of each robot joint motor can be determined, and the joint motor can be selected properly so as to provide the necessary theoretical support for the development of the actual robot physical prototype.

6. Conclusion and Future Work

6.1. Conclusion

(1) A basic configuration of a four-wheel-driven and four-arm mobile robot for the maintenance task of double-split transmission line spacer bar replacement has been proposed, its virtual prototype and principle prototype mobile platform have been developed, and the corresponding operation tools and complete operation motion planning have also been designed.

(2) Compare with the existed research, the mechanical structure parameters of the robot were effectively optimized through the robot kinematics analysis, and the weight of the robot was reduced by 12%. The robot’s electrical control parameters were effectively optimized through robot dynamics analysis, and robot costs were reduced by 15%.

(3) The robot kinematics and dynamics numerical analysis simulation experiments verify that the designed robot system can meet the requirements of the workspace and the force control requirements between the operation manipulator and the spacer bar during the replacement operation, which lays a theoretical foundation for the robot physical prototype development.

6.2. Future Work. The live maintenance robot and its operation environment of high-voltage transmission lines constitute a complex rigid-flexible coupling system. Although some progress has been made in key technologies related to such robots, there is considerable space for improvement to meet the basic requirements of complex and
changeable HVTL environments. Based on research on live maintenance robots, the authors’ future research in the area will focus on the practical needs in the context of scientific and technological development to implement human-machine integration to enable the live maintenance robot to effectively perform maintenance operations. In this way, the robot can improve the operation and maintenance of power systems, thereby, to realize power system automation.

Data Availability

Data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by the China Textile Industry Federation Science and Technology Guiding Project (Project ID: 2019053), 2019 Opening fund for Hubei Key Laboratory of Digital Textile Equipment (DTL2019010), and the Hunan Province Key Laboratory of Intelligent Live Working Technology, Equipment and Live Inspection and Intelligent Operation Technology State Grid Corporation Laboratory Opening Fund (ID: 2019KZD1005).

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