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Mechanism Configuration and Innovation Control System Design for Power Cable Line Mobile Maintenance Robot

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SUMMARY
High-voltage power cables are important channels for power transmission systems. Their special geographical environment and harsh natural environment can lead to many different faults. At present, such special operations in dangerous and harsh environments are performed manually, which not only has high labor intensity and low work efficiency but also has great personal safety risks. In order to solve such difficult problems, this paper studies the power maintenance robot for insulator string replacement, spacer replacement, damper and drainage plate maintenance; the basic configuration and the operation motion planning have been proposed; and the virtual prototype of the inspection maintenance robots has been developed, and then the mechanical structure of the robots has been optimized by the robot kinematics modeling and analyzed the working space based on the Monte Carlo method. The system platform, operation function, structural characteristics and related key technologies involved in the robot system development were systematically summarized; the deep integration point for the robot technology with big data, cloud computing, artificial intelligence, and ubiquitous power Internet-of-Things technologies was also discussed. Finally, the physical prototype of the insulator replacement, drainage plate tightening, and damper replacement operation robot has been developed; several experimental tests on a 220 V live line have been conducted so as to verify the robot engineering practicality; and the main development and future research direction have also been pointed out at last.

KEYWORDS: High-voltage line; Power inspection maintenance robot; Mechanism configuration; Physical prototype; Ubiquitous Power Internet of Things (UPIOT).

Introduction

During the long-term operation, high-voltage transmission lines (HVTLs) are easily affected by many factors in the operation environment; live operation is an important technical way to eliminate the faults in transmission lines. However, live maintenance is a challenging and dangerous work; at

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present, the relevant tasks can be performed only through the cooperation of several operators on and below the tower, which has the drawbacks of requiring considerable human labor; it not only poses safety risks, moreover, because of the complexity and diversification of the power grid, but also a significant number lines are not susceptible to live maintenance operation because of the tight safety distance. Facing this complex and dangerous environment, the limitations of manual live operation become increasingly prominent. The live maintenance robot has emerged in recent years, which travels on the transmission line and can reach dangerous areas where human worker cannot reach. Moreover, the use of the robot avoids risk to human personnel and enhances the operation reliability of the power grid.

Therefore, the live working robot can assist with or even replace manual live maintenance operation and solve the problem of multitask-oriented live maintenance in cases of insufficient electrical distance, thus improving the efficiency of live maintenance and reducing the labor cost and risk to workers. At the same time, the structural design of the robot is the primary basic technical problem for the development of the robot system and the current line structure is similar and different, with there are many types of operations. Research on the configuration of robots for different lines and different tasks for live working robot has significant theoretical and practical values for the automation of electric power systems.

1. Research Status of Inspection Maintenance Robot for Transmission Lines

The power line maintenance inspection robots can be mainly divided into three types, inspection only, maintenance only, and both inspection and maintenance; for example, Japan, Europe, and United States have studied live maintenance automation technology and developed a variety of automation devices for different kinds of operation tasks by using intelligent operation terminal tools relied on insulated bucket arm trucks.[1,2] The representative robots in this field include the optical fiber composite overhead ground mobile robot which is developed by Tokyo Electric Power Company,[3,4] the Phase series robot which is developed by Japan Kyushu Electric Power Company,[5–7] subsequently, the Manitoba University in Canada[8] has developed the tactile remote control manipulator, and Canada Quebec Hydropower Research Institute[9] has developed "LineScout robots" which can perform maintenance with obstacle functions. After years of development, more and more new technologies are being applied to the inspection, operation, and maintenance of HVTL through the LineScout platform. The Korea Electric Power Research Institute[9] has developed an insulator detection robot for the 345 kV AC transmission line, the basic configuration of a bolt tightening robot has been developed by India Welol University of Technology,[11] the bolt tightening can be carried out through the double mobile arms, the working manipulator and the fixed arms have been designed as a whole, wherein one arm fixes the hexagonal bolt and the other completes the tightening operation by rotating the sleeve motor. Additionally, American Electric Power Research Association,[12] Spain,[13] Ukrainian Electric Power Research Institute and Wenicha Polytechnic University[14] have also developed robots for transmission lines live maintenance operations.

The representative research institute on power line robots in China includes the Shandong Electric Power Research Institute,[15,16] it has developed a prototype which can be applied to 10 kV voltage levels, and the institute has also developed a 660 kV Ultra-high-voltage (UHV) power grid insulator detection robot which can carry out horizontal and vertical insulator detection. The wire repair robot and 500 kV UHV AC transmission line double-tension insulator string detection robot were developed by Chinese Academy Science Shenyang Automation Institute.[17,18] The State Grid Hunan Electric Power Company[19–21] has developed a series live operation robots for transmission lines, which are called the "Dream Series robot", this series robots can implement damper replacement, and the research on this kind of robot has strong reference value for the design of a tension clamp drainage plate bolt tightening robot. From 2007 to 2013, Wuhan University developed autonomous inspection robots which can cross obstacles along the ground line[21] and inspection robots which can cross obstacles along both wires and the ground line.[22] Taking the inspection robot as a mobile platform, a new deicing robot for HVTL has also been developed; the robot has a double-arm wheel suspension structure, wherein the deicing tool is mounted on the mobile arm; the robot can detach ice from overhead HVTL. Additionally, Wuhan University has developed a HVTL tree-trimming robot, the robot consists of a mobile platform and an operation system, the mobile platform travels along the transmission line, and the operation system can carry a super-long insulated arm, which can carry out tree trimming while walking online. However, the robot can cross only a certain type dampers

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and with a complex robot up–down line process; additionally, the tree-trimming mechanism needs to be further studied[23,24] in the future.

From the above analysis, the configuration of mobile robots is very important and the basis for the robot physical prototype development. In order to complete the established typical operation functions, according to whether the mechanical arm has independent movement. It can be divided into two-arm,[25,26] three-arm,[27,28] and four-arm[29,30] working mechanisms; according to different single-wire and multi-split circuit structures, it can be divided into wheel drive[31,32] and track drive[33,34] robot mobile platform mechanism. Through analysis, it can be seen that the mainstream of domestic and overseas power maintenance robot mechanism configuration is a multi-arm robot system composed of a walking arm and a working arm formed by a mobile robot walking on a transmission line and carrying a working manipulator. Therefore, from the aspect of robot mechanical structure, it is an urgent need to develop a new type of robot mechanism that can meet the needs of multi-line and multi-task operations for different tasks and adapt to different voltage levels and multi-split transmission lines. Based on the above, this paper designs different mechanical structures of power cable robot for single transmission line, double-split transmission line, four-split transmission line maintenance, and UHV multi-split reconfigurable robot. The corresponding operation motion planning and the system virtual prototype have been proposed, all which lays a solid theoretical foundation for the physical prototype development of UHV multi-split reconfigurable mobile robot oriented to multitasks.

2. Configuration of Inspection Maintenance Robot for Different Operation Tasks

2.1. Design of single-split transmission line insulator string maintenance robot

The suspension insulator string is an important line fitting which is connected to a transmission line through suspension clamps. The insulators are connected with each other through bowl head hanging broad. The key to replace insulator string is to roll out the joint connection component W pin using W pin pushing block, the W pin is located in bowl head notch, the final step is to push the new insulator string ball head into the bowl head notch and push-in W pin, so that the free state insulator string can be fixed and an entire replacement can be completed. In the whole process, the robot is mainly responsible for clamping insulators, pushing W pin in and out, pushing ball head in and out, while artificial work mainly includes tightening or loosening wire and insulator replacement. In the man–machine coordination mode, the insulator string replacement operation can be achieved; the configuration, entity model, and online operation of insulator maintenance robot are shown in Fig. 1.

2.2. Design of double-split transmission line spacer maintenance robot

The spacer bar maintenance robot has double operation arms, among which the operation arm 1 is arranged at the front end of the body, far away from the side of the body, with two Degree of freedom (DOF) of stretch joint and rotation joint, which can transport the operation arm 1 to the working position, the operation arm 2 is arranged at the front end of the body, close to the side of the body, it has three DOF, namely, stretch joint, vertical joint, and horizontal, which can bring the operation arm 2 to the working position. The manipulator 1 is equipped with a clamping mechanism with two sets of clamping claws, the opening diameter of the clamping claw is equal to the diameter of the spacer bar, and the motor drives the clamping claw to shrink and clamp the spacer bar. A bolt tightening mechanism is installed at the end of the working arm 2 so as to tighten and loosen the spacer bolt. The complete virtual prototype of spacer maintenance robot and its online operation are shown in Fig. 2.

2.3. Design of four-split transmission line damper maintenance robot

The four-split transmission line damper maintenance robot adopts the mode of mobile platform with manipulator to carry out transmission line maintenance. Wherein, the configuration and entity model of the mobile robot and online operation are shown in Fig. 3. It is mainly composed of robot body, double mobile arms, double mobile wheels, clamping mechanism, supporting mechanism, pitch mechanism, and bolt tightening mechanism. Operation arm 1 and operation arm 2 are installed on the horizontal slide, with rotation, stretch, and horizontal three DOF movements. The live line damper maintenance for the four-split transmission line can be realized by holding the damper clamping mechanism with the operation arm 1 and tightening or loosening the damper bolt with the operation arm 2.

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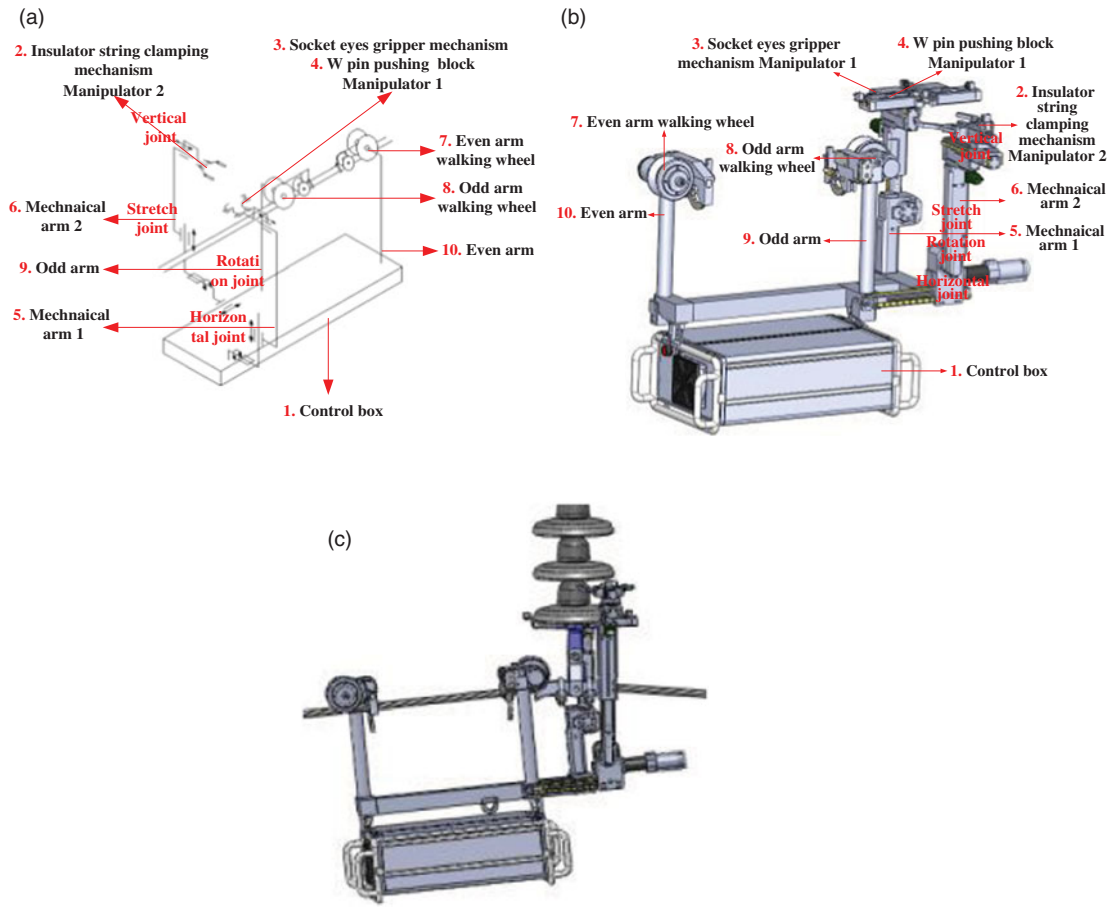


Fig. 1. Configuration entity model and online operation of insulator maintenance robot: (a) Configuration, (b) Entity model, and (c) Robot online operation.

2.4. Design of four-split transmission line drainage plate maintenance robot

The maintenance robot for the four-split transmission line drainage plate adopts the mode of mobile platform with manipulator to carry out the transmission line maintenance. The configuration and entity model of the mobile robot is shown in Fig. 7. It is mainly composed of robot body, double mobile arms, double mobile wheels, bolt fixing mechanism, and bolt tightening mechanism. Operation arm 1 and operation arm 2 are installed on the horizontal slide, with rotation, stretch, and horizontal three DOF movements. By fixing the bolts of the drainage plate with the operation arm 1 and tightening the bolts with the operation arm 2, the live maintenance operation of the four-split transmission line drainage plate can be realized.

2.5. System design for UHV multi-split reconfigurable robot

In order to realize the "one machine and multi-use" function of the robot platform, different transmission line maintenance operations can be completed by reconstructing different operation manipulators of the mobile robot. In this paper, the basic configuration and manipulators reconstruction mode of the UHV multi-split reconfigurable robot have been designed as shown in Fig. 5. The robot system is composed of mobile platform with operation manipulators and uses the same robot body to reconstruct different operation manipulators for different maintenance tasks. Fig. 5(a) shows the entity model of the robot mobile platform. Fig. 5(b) shows the two-group operation manipulator. The replacement and maintenance robot of damper can be obtained after the first group manipulator reconstruction, which can realize live maintenance of damper for four-split transmission line. The robot fixes and tightens the drainage plate bolts after the robot reorganizes the second group manipulator, which can realize the live maintenance of the drainage plate for the four-split transmission line.

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Table I. Link parameters and joint variables of operation arm.

No$_i$	Length (a_{i-1}/mm)	Twist angle (α_{i-1}/°)	Basis (d_i/mm)	Joint angle (θ_i/°)	Joint variable range
1	534	0	Vertical d_1	0	5∼267 mm
2	173	90	0	Rotation θ_1	0∼90°
3	295	0	Stretch d_2	0	5∼241 mm
4	66	90	0	Pitch θ_2	0∼90°

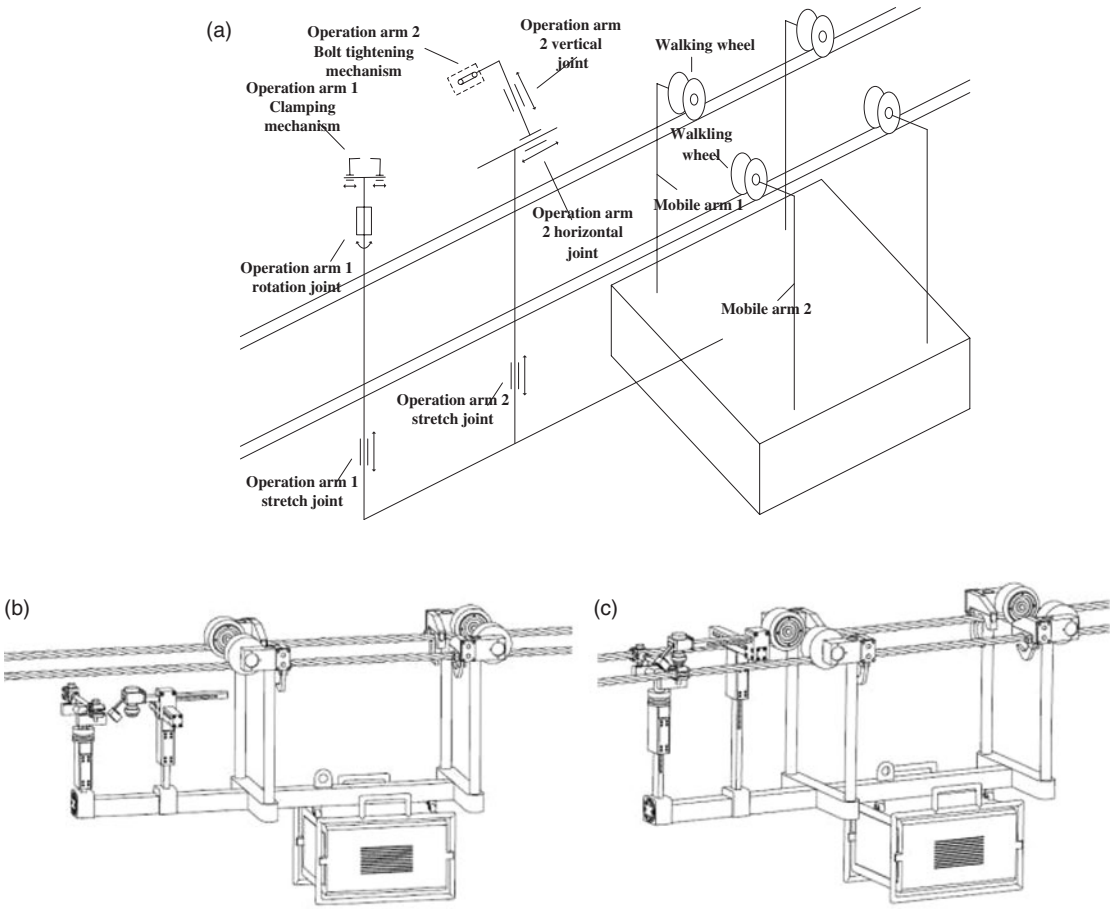


Fig. 2. Configuration entity model and online operation of spacer maintenance robot: (a) Configuration, (b) Entity model, and (c) Robot online operation.

3. Kinematics Modeling and Analysis of Mobile Operation Robot System Design

3.1. Establishment of coordinate system

Taking the damper replacement four-wheel mobile robot as an example so as to perform the robot kinematics modeling and analysis and to establish the coordinate system {0}–{4} according to the D-H method as shown in Fig. 6, wherein the base coordinate system {0} is established at the initial posture of the operation arm 1, the link coordinate system {1} is established at the vertical joint of the operation arm 1, the link coordinate system {2} established on the rotation joint of the operation arm 1, the link coordinate system {3} is established on the stretch joint of the operation arm 1, and the link coordinate system {4} is established on the pitch joint of the operation arm 1, the D-H parameters of the connection rod are shown in Table I.

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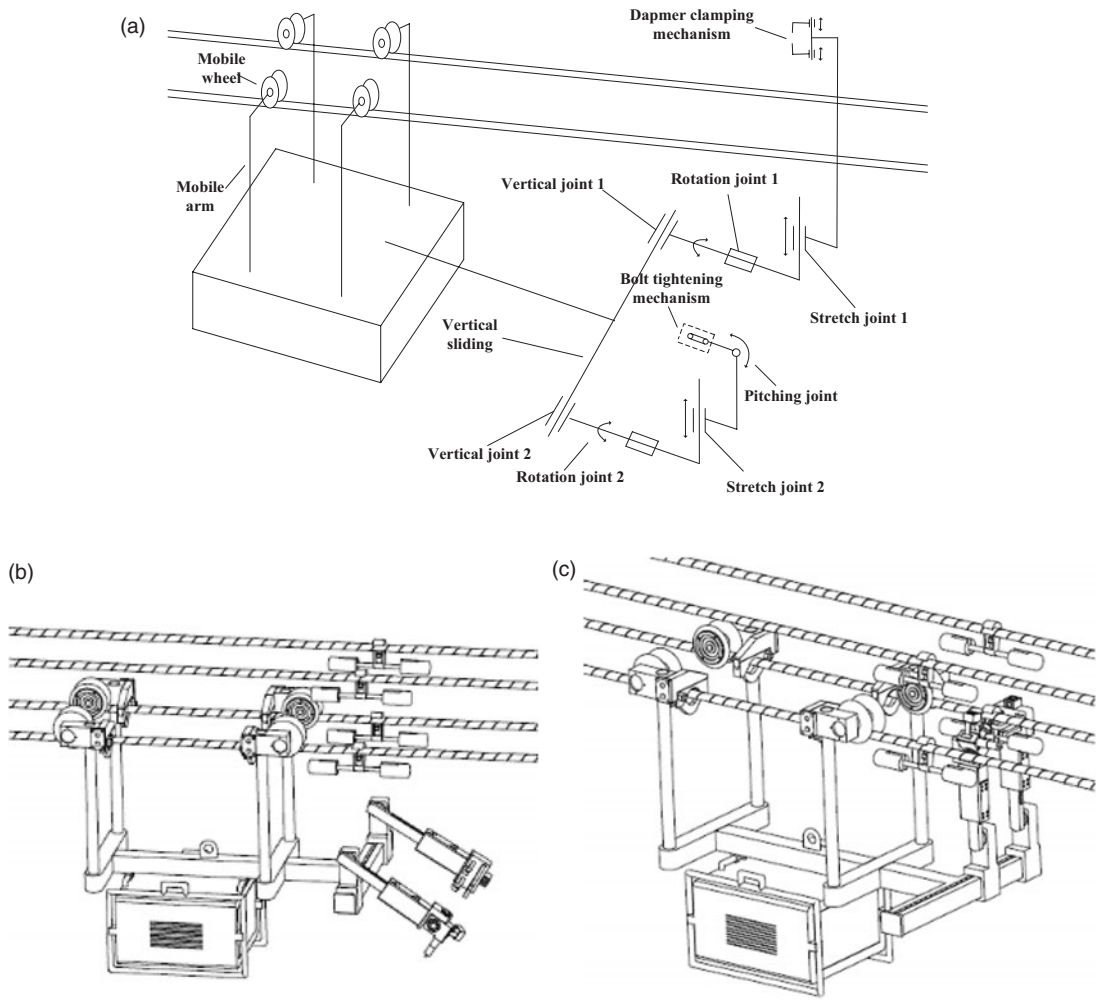


Fig. 3. Configuration entity model and online operation of damper maintenance robot: (a) Configuration, (b) Entity model, and (c) Robot online operation.

3.2. Kinematics positive solutions

The positive solution of the robot kinematics is to solve the posture of the end effector through the known joint variables and the linkage offset parameters. Set the posture matrix with respect to the base coordinate system when tightening the damper bolts as Eq. (1).

$$P = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

According to the D-H regulation, through the homogeneous transformation matrix multiplication so as to obtain the robot manipulator posture matrix as Eq. (2).

$$P = \begin{bmatrix} \cos\theta_2 & 0 & \sin\theta_2 & 267+d_1 \\ \sin\theta_1 \sin\theta_2 & \cos\theta_1 & -\sin\theta_1 \cos\theta_2 & -\sin\theta_1\ (534+d_2) \\ -\cos\theta_1 \sin\theta_2 & \sin\theta_1 & \cos\theta_1 \cos\theta_2 & \cos\theta_1\ (534+d_2) \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

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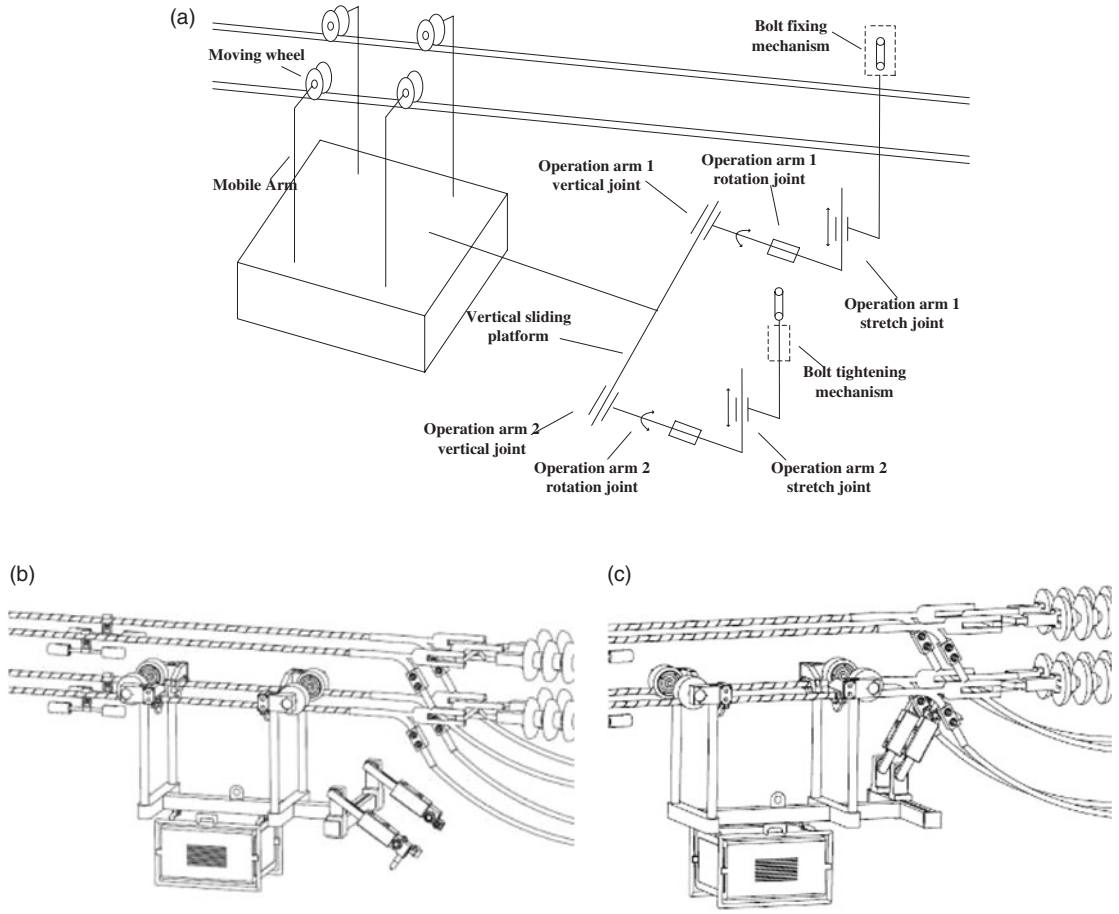


Fig. 4. Configuration entity model and online operation of drainage plate maintenance robot: (a) Configuration, (b) Entity model, and (c) Robot online operation.

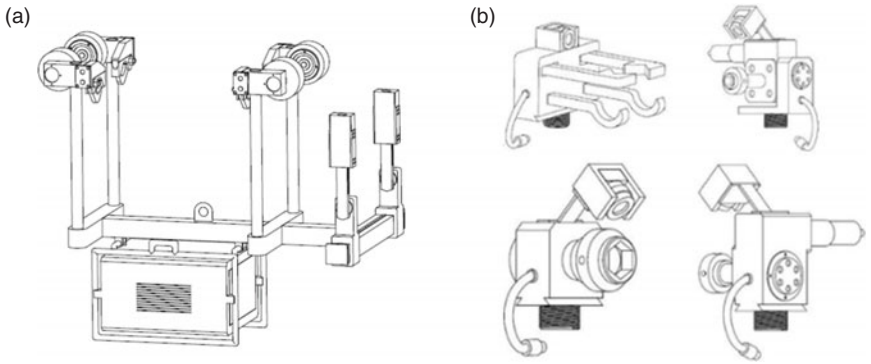


Fig. 5. Reconfigurable maintenance robot and its reconstruction method: (a) Robot mobile platform, and (b) End effector.

Therefore, the positive solution of kinematics is Eq. (3).

$$\begin{aligned}
&n_x = \cos\theta_2, \quad n_y = \sin\theta_1 \sin\theta_2, \quad n_z = -\cos\theta_1 \sin\theta_2;\\
&o_x = 0, \quad o_y = \cos\theta_1, \quad o_z = \sin\theta_1;\\
&a_x = \sin\theta_2, \quad a_y = -\sin\theta_1 \cos\theta_2, \quad a_z = \cos\theta_1 \cos\theta_2;\\
&p_x = 267{+}d_1; \quad p_y = -\sin\theta_1\,(534{+}d_2); \quad P_z = \cos\theta_1\,(534{+}d_2).
\end{aligned} \tag{3}$$

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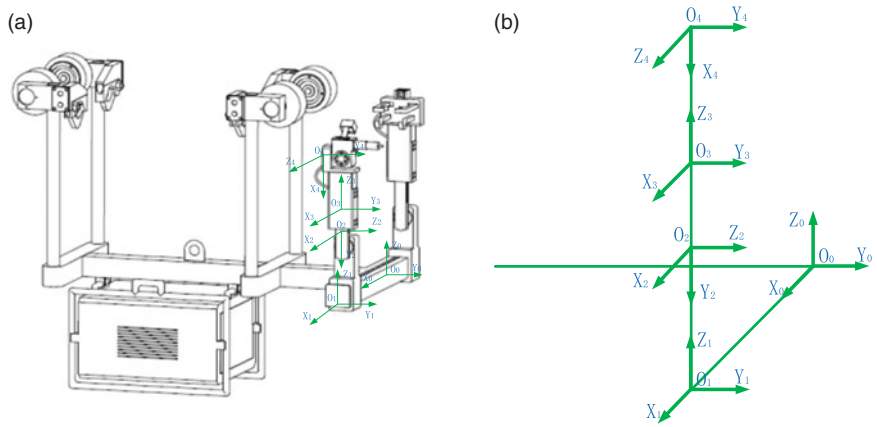


Fig. 6. Establishment of D-H coordinate system: (a) Robot D-H coordinates and (b) D-H coordinate system diagram.

3.3. Kinematics inverse solutions

The inverse solution of the robot kinematics is the reverse process of the positive solution, it can be used to solve the variable values and link offset parameters of any joint at any time, and the inverse kinematics solution of the robot manipulator can be obtained as Eqs. (4) and (5).

$$P = {}^{0}_{1}T\ (d_1)\ {}^{1}_{2}T\ (\theta_1)\ {}^{2}_{3}T\ (d_2)\ {}^{3}_{4}T\ (\theta_2) \tag{4}$$

$$\begin{cases} \theta_1 = \arccos o_y = \arcsin o_z \\ \theta_2 = \arccos n_x = \arcsin a_x \\ d_1 = p_x - 267 \\ d_2 = -\frac{p_y}{o_z} - 534 = \frac{P_z}{o_y} - 534 \end{cases} \tag{5}$$

4. Robot Innovation Control Architecture Based on Ubiquitous Power Internet of Things

The traditional control architecture of the power operation robot and the entire power system consists of different transmission lines. Each conductor is equipped with a maintenance robot, and each robot walks on the field power line to maintain power cable fittings and faults. Its underlying operational status can be acquired by a signal processing unit and industrial A/D sample cards and then can be transmitted on a 4G wireless network to the robot control base station in the monitor center of the operation department. The transmission line monitor center is connected with the monitor center of the municipal bureau through a public network so as to share resources and information. At the same time, the monitor center can send control instructions to the field power cable line through the wireless network so as to implement the robot remote motion control. The control architecture of the UP-IOT for transmission lines can be implemented through the way of space-earth cooperation, which mainly includes satellites in the air, unmanned aerial vehicles online, robots, ground control base stations offline, all which are composed of three-dimensional control mode; the new innovation control structure diagram is shown in Fig. 7. Synthetic Aperture Radar (SAR) remote sensing satellite can be used in the air to realize wide-area and high-efficiency monitoring of foreign bodies and tower tilt on transmission lines. Robot combined with UAV patrol operation mode can be adopted on transmission line. On the ground, the monitor device on the transmission line can be used as the edge calculation device. Form the above analysis, it forms a power grid intelligent operation and maintenance platform, which is composed of transmission line, operation environment, robot and monitor center. In this platform, the function of the robot is to assist or replace manual work, which can greatly reduce operational risks, improve operational efficiency, and realize intelligent management and operation of power grid system, and the innovation control architecture based on Ubiquitous Power Internet of Things can be obtained from traditional control architecture and as shown in Fig. 7.

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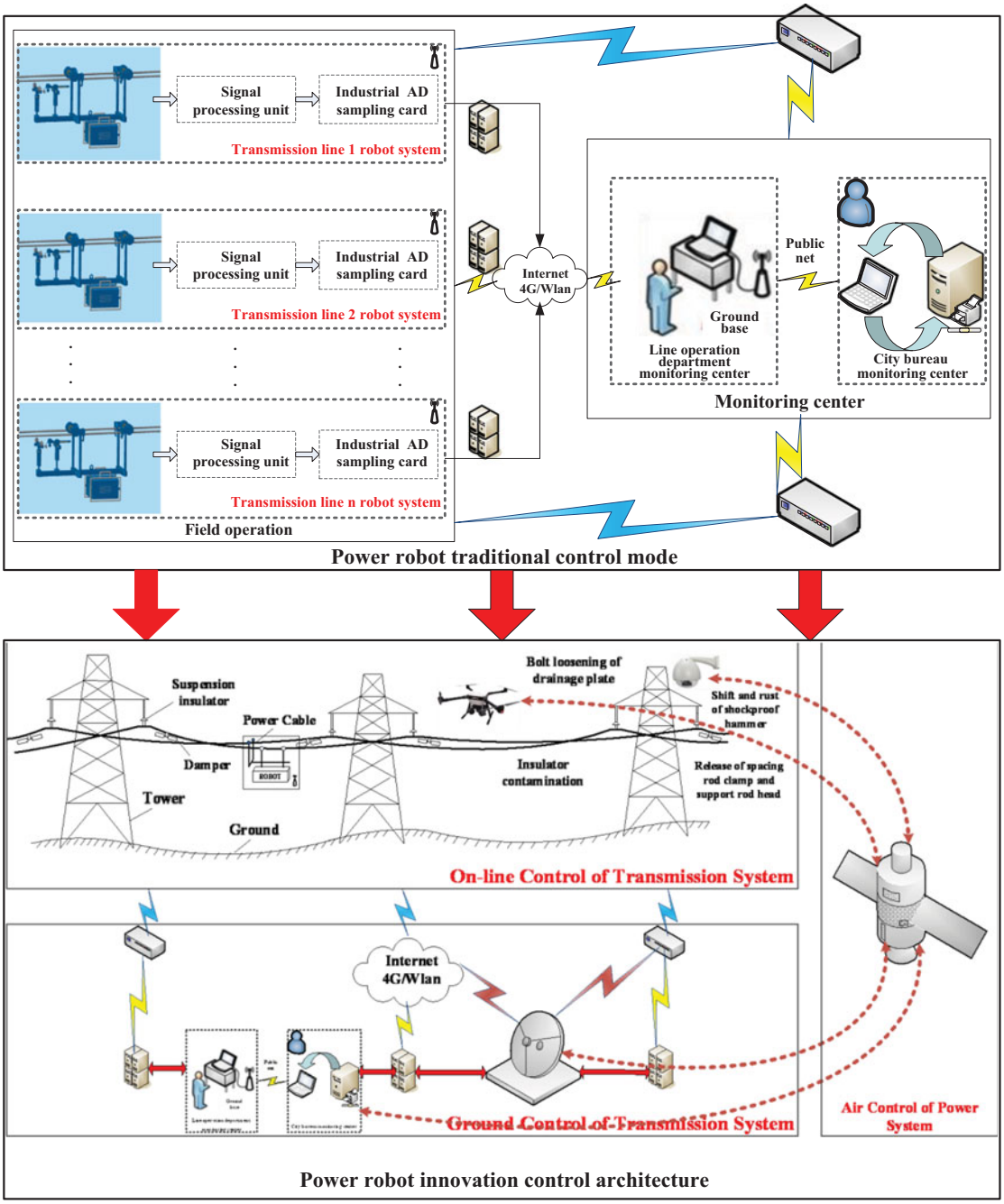


Fig. 7. Innovation control architecture for power operation robots.

5. Simulation Experiment

5.1. Simulation analysis of robot mechanical structure parameters

The simulation analysis for the manipulator working space and the corresponding robot motion planning is the basis for the design and optimization of the robot mechanical configuration. Taking the damper replacement robot as an example, based on the robot kinematics analysis, the dual arm joint motion planning in the MATLAB environment can be obtained as shown in Fig. 8(a); through the joint motion control, the damper replacement operation end effector can be brought into the working space and meet the requirement of the manipulator motion control. Additionally, the Monte Carlo method can be used to simulate and analyze the robot working space. The Monte Carlo method uses the probability phenomenon as the research object and calculates the statistical value according to the sample survey method so as to estimate the unknown characteristic. The robot working arm moves

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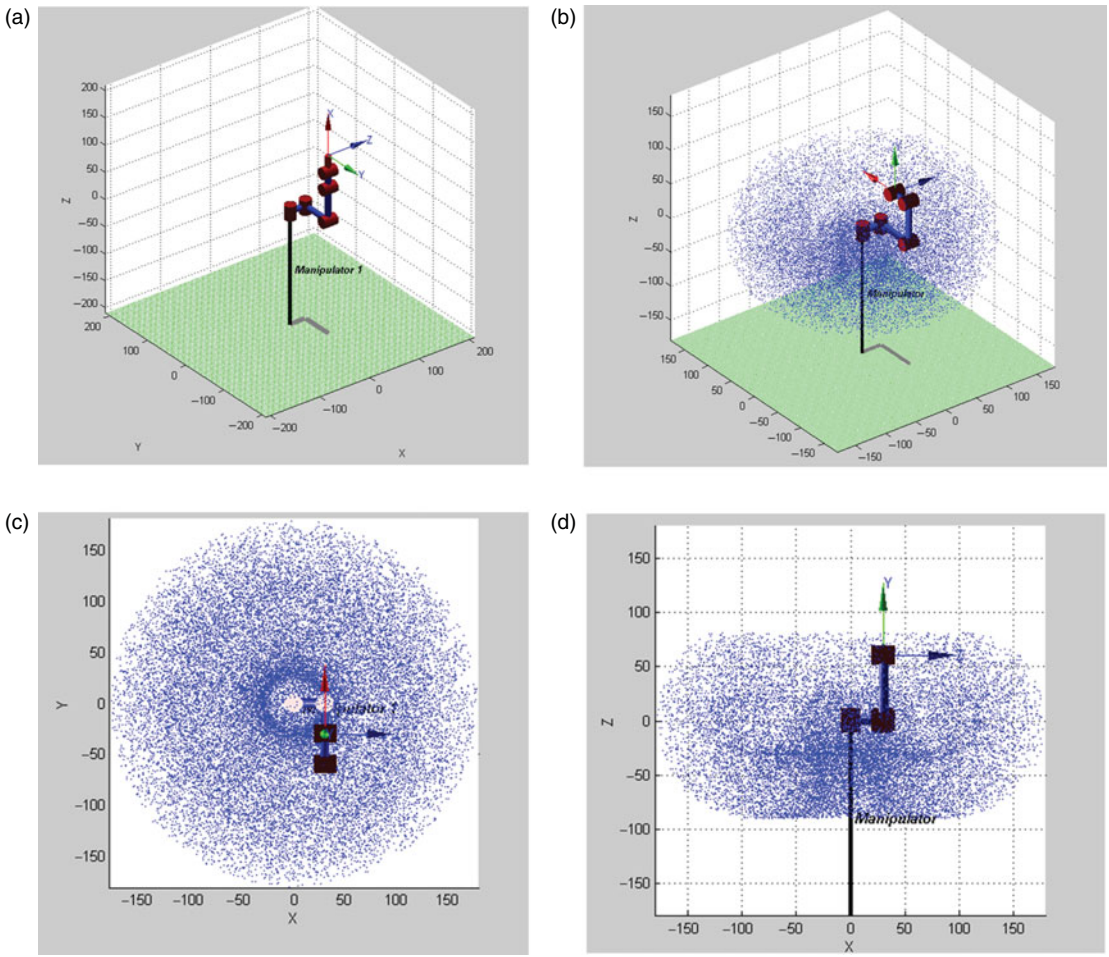


Fig. 8. Damper replacement robot joint motion and workspace simulation: (a) Joint movement, (b) X-Y-Z point cloud, (c) X-Y point cloud, and (d) X-Z cloud

according to the planned route in a specified range, and the end effector randomly traverses the points during the movement; therefore, the set of all points is the robot workspace. In the MATLAB environment, the Monte Carlo point cloud diagram of the manipulator workspace is shown in Fig. 8(b), (c), (d).

From Fig. 8(b), (c), (d), it can be can concluded that the range of the working space in three directions is $x \in [-150, 150]$ mm, $y \in [-150, 150]$ mm, $z \in [-90, 90]$ mm, respectively. According to the link parameters and joint variables of the robot working arm, the robot maximum stroke in the X axis direction is 267 mm, the robot maximum stroke in the Y axis direction is 241 mm, and the robot maximum stroke in the Z axis direction is 167 mm. From the experimental data, it can be concluded that the manipulator link d_1 has a 33 mm surplus, connection rod d_2 has a 59 mm surplus, and the machining error that does not exceed this value can be allowed without affecting the robot completing the live maintenance work. The end effector work space calculated by the Monte Carlo method can completely cover the actual work space, and the point cloud distribution of each plane projected cross section is evenly distributed, there are no holes or cavities, the simulation results meet the expected standard and the correctness of the robot workspace has also been verified.

6. Physical Prototype Development and Future Trends of Power Cable Robot

6.1. Development of physical prototype of power maintenance robot

The key to replace insulator string is to roll out the joint connection component W pin using W pin pushing block, and the W pin is located in bowl head notch. The final step is to push the new insulator string ball head into the bowl head notch and push-in W pin so that the free state insulator string can be fixed and an entire replacement can be completed. In the whole process, the robot is

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Fig. 9. Power mobile operation robot online physical prototype: (a) Insulator replacement robot, (b) Bolt tightening robot, and (c) Damper replacement robot.

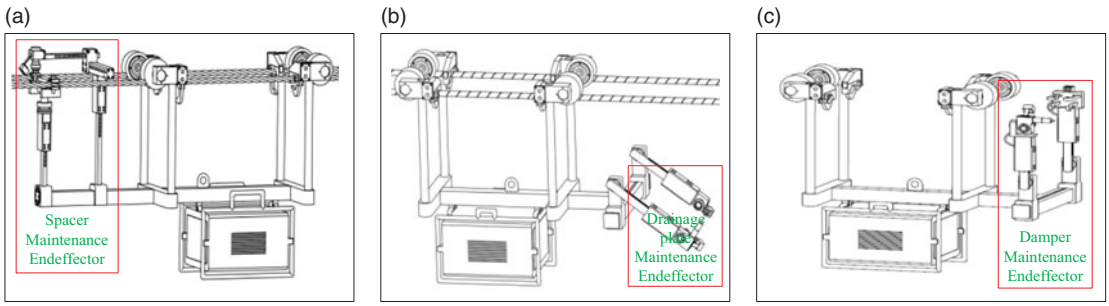


Fig. 10. Virtual prototype model of multi-tasks reconfigurable power maintenance robot: (a) Double split spacer maintenance, (b) Double split drainage plate maintenance, and (c) Quad splitdamper maintenance

mainly responsible for clamping insulators, pushing W pin in and out, and pushing ball head in and out, while artificial work mainly includes tightening or loosening wire and insulator replacement. In the man–machine coordination, the replacement operation of insulator strings can be achieved; the developed robot physical prototype and its field operation test are shown in Fig. 9(a).

In the process of bolt tightening operation, at first, the robot walks on transmission line till its walking wheel detecting and then localizing to press-connection pipe; in the meantime, the robot walking wheel brakes and the double arm begins to work after releasing the double jaw clamping transmission line. Second, the joint movements of manipulator 1 can be adjusted, so that sleeve 1 can accurately align to bolt head and fix the bolt head, after that the joint movements of manipulator 2 is adjusted, so that sleeve 2 can hold nut and then the tightening and loosening nut can be realized by rotation of end tool motor. The bolt tightening can be achieved, the developed robot physical prototype and its field operation test are shown in Fig. 9(b).

The replacement of damper operation can be completed mainly by the bolt tightening mechanism and the damper clamping mechanism, wherein the bolt tightening mechanism is responsible for tightening (or loosening) the clamp, while the damper clamping mechanism is responsible for holding the new (or old) damper and bring it into (or out of) the working space. The damper replacement can be achieved through the all joints coordination operation, and the entire working process can be completed by the robot without any outside manual intervention, the replacement operation of damper can be achieved, the developed robot physical prototype and its field operation test are shown in Fig. 9(c).

6.2. Development of robot virtual prototype for UHV multi-split transmission line

In order to continuously adapt to the structure of transmission lines, we have developed virtual prototype of single conductor maintenance robots with obstacle crossing functions, virtual prototype of double-split transmission line spacer and drainage plate maintenance robots with no obstacle crossing functions, and virtual prototype of quad-split transmission line damper and drainage plate maintenance robots with no obstacle crossing functions, all the robots' virtual prototypes are shown in Fig. 10, which can be divided into two categories, namely two-wheel-drive robot and four-wheel-drive robot; compared with two-wheel and three-wheel robot, four-wheel robot is more adaptable to the transmission line environment and more stable in operation. This research has important theoretical significance and practical application value for the development of UHV multi-split mobile robots physical prototypes.

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7. Conclusion

The live maintenance robot and the HVTL working environment constitute a complex rigid-flexible coupling system. Although some achievements have been made in the key technologies of live maintenance robots, there is still many works to be done so as to meet the basic requirements of complex and changeable line environment in the practical application. Based on the existing research results of live maintenance robots, the follow-up research will focus on the practical application needs and the frontier scientific technological development and truly realize the human–machine integration among live maintenance robot–human working environment. Only in this way, the robot can better serve the operation and maintenance of the power system.

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