Research on a Novel Inspection Robot Mechanism for Power Transmission Lines*

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Abstract—A novel mechanism for power transmission line inspection robot is presented according to the requirements of inspection tasks and characteristics of obstacles on power lines. Its configuration is introduced, and the kinematics equations and statics model are established. Then, the motion sequences for crossing the strain clamp are planned. Furthermore, the simulation of the navigation of the strain clamp has been carried out. The simulation results demonstrate that the mechanism has such characteristics as good motion stability, strong loading capacity and excellent obstacle negotiation capability.

I. INTRODUCTION

Transmission grids, as strategic assets, need to be operated in a safe, predictable, and reliable way [1-4]. In recent years, the research on the power transmission line inspection robots has become a hot topic. The main research interests focus on the mechanism optimal design, the control system design, the power supply, fault detection methods, and EMI/EMC etc. Above all, it is very important to design a proper mechanism with excellent locomotion and navigation performance.

HiBot Corporation and Tokyo Institute of Technology have developed a robot named Expliner [5, 6] which has a carbon-fiber structure with a T-shaped base and a 2-DOF manipulator. This robot can inspect and cross the obstacles on transmission lines of 600kV. The robot consists of two drive units, two vertical rotary joints, two 2-DOF operating arms and an electrical cabinet. Quebec Hydro Institute of Canada has developed a new kind of robot LineScout. The LineScout, which can inspect live transmission lines of 315kV, includes three separate parts: the guide wheel frame, arm frame and center frame. Morozovsky, designed a small inspection robot SkySweeper. SkySweeper is V-shaped with a motor-driven “elbow” in the middle and its ends are equipped with clamps that open and close as necessary to move it down the line, inch by inch[7].Trevor Lorimer and Ed Boje designed a simple robot which is able to cross strain tower. The robot is a series of links with a gripper at each end. When one gripper is detached from the line, the robot may be thought of as a serial manipulator, with the attached gripper being the base and the detached gripper being the end effector [8].

According to the characteristics of the 110kV transmission line environment and the requirements of inspection tasks, a novel inspection robot mechanism is presented based on the parallelogram mechanism. The novel mechanism consists of two wheeled locomotion mechanisms, dual arms, a frame and centroid adjustment mechanism, which can move along the conductors and negotiate a variety of obstacles on the 110kV power transmission lines. This paper is organized as follows: The overview of the completed research work and the environment characteristics of 110kV transmission line are presented in Section I and II, respectively. Then, the inspection robot configuration is introduced in Section III. The kinematics and the statics of the robot are analyzed in Section IV. The simulation and analysis is described in details in Section V. Finally, the conclusion is given in Section VI.

II. ENVIRONMENT DESCRIPTION

According to the inspection task requirements for 110kV power transmission lines, the inspection robot needs to move along the power transmission line. navigate the obstacles, carry visible light camera and infrared camera to complete inspection tasks.

The environment of the 110kV power transmission lines is very complicated, where there are straight towers, strain towers, conductors, OGWs, vibration damper and other electric power equipment. A general schematic of 110kV transmission line is presented in Fig. 1. There are many obstacles on conductors such as vibration dampers, suspension clamps, strain clamps and jumper. Strain towers in the transmission grid are common as they are used to change in direction due to terrain or avoidance of privately owned land. A jumper is a short length of conductor, not under
mechanical tension, making an electrical connection between two separate sections of a line. Jumpers at strain towers are one of the most complex obstacles on the line to traverse; they are the flexible cables which are not as stiff as main spans and appear under complex spatial curves. At the end of the jumper, its slopes are approximately vertical, and their layout varies considerably from tower to tower. In order to accomplish the inspection task, the robot must have the ability to navigate the obstacle around straight line tower and the strain tower.

As shown in Fig. 2, the robot should have the ability to move on the jumper since its span is very long. Because of the flexibility and un-tensioning, the posture of the jumper cable will change when the robot moves on it. Moreover, there are many different obstacles on the jumper such as strain clamps and parallel groove clamps. The robot mechanism must be of high stability, simplicity, and navigation capability. When gripping the jumper, the robot cannot cause damage to the conductor. Because the inspection tasks are carried out on energized lines, so reducing the electromagnetic effect on the performance of the robot is very important requirements. The size of the robot should be minimized so that a safe insulation distance from ground and other circuits are maintained.

The mechanism designed for inspecting conducts should perform the inspection tasks as well as a trained human operator. Based on the requirement of the inspection tasks and the environment characteristics of 110kV transmission lines, the mechanism should be developed with the following functions:

1. Moving on the conductor steadily and rapidly;
2. Navigating different obstacles, such as vibration damper, strain clamp, the jumper.
3. Climbing a conductor at a 80-deg slope;
4. Keeping steady during moving on the conductor and navigating obstacle.
5. Compact construction.

III. MECHANISM CONFIGURATION

Fig. 3 is a schematic diagram of the inspection robot. The robot consists of two wheel locomotion mechanisms, two arms, a centroid adjustment mechanism and an electrical box component. The wheeled locomotion mechanism is applied to ensure robot can move rapidly on the conductors. Each locomotion mechanism consists of two wheels and a gripper. Each arm includes a rotation joint, a translational joint and a parallelogram mechanism. With the help of parallelogram mechanisms and the centroid adjustment mechanism, the body of the robot can keep horizontal, which improves the stability of navigating obstacles.

![Figure 3. The mechanism schematic](image)

The sketch of the inspection robot is shown in Fig.4. \( \Theta_1 \) and \( \Theta_{10} \) are revolving joints. When the robot navigates the strain clamp, the fore-gripper or the rear-gripper can rotate to grasp the jumper. \( d_3 \) and \( d_6 \) are translational joints which provide a linear sliding movement for the fore arm or the rear arm. Their functions are to go up or down for fore arm and rear arm. When the fore arm or the rear arm hangs on the conductor in obstacle navigation process, the rear arm or the fore arm is on or off the conductor. \( \Theta_5 \) and \( \Theta_8 \) are also revolving pairs. When the fore arm hangs on the conductor and the rear arm is off the conductor, the body of the inspection mechanism can rotate through the axes under the \( \Theta_3 \) and \( \Theta_6 \) driving and implement obstacle navigation. \( \Theta_4 \) and \( \Theta_9 \) are revolving joints which drive the four-bar mechanism. \( d_{11} \) is a prismatic joint for centroid adjustment. The center of gravity can be located under the fore arm or the rear arm by intentionally actuating the robot joints when the robot is navigating obstacles. The center of mass of the robot is always located at the bottom of the fore arm or rear arm by adjusting in obstacle-negotiation sequence.

In a word, the robot can move on the conductor steadily and rapidly by using the wheeled locomotion mechanism. The wheel-arm and the centroid adjustment mechanism ensure the robot has obstacles crossing ability and climbing ability. Besides, the parallelogram mechanism improves the overall stiffness, and enhances the load capacity of the robot.
IV. KINEMATICS AND FORCE ANALYSIS

A. Kinematics modeling for the inspection mechanism

When the mechanism needs to navigate the obstacle, the gripper of the arm should grasp the conductor. When one gripper is detached from the line, the mechanism may be thought as a serial manipulator, with the attached gripper being the base and the detached gripper being the end effector. The gripper plays a fixed role in the obstacle negotiation sequence, so the freedoms of the wheel and the gripper should be neglected in the kinematics modeling.

\[ \theta_1 + \theta_2 = -\pi; \] similarly, the joint variables \( \theta_6 \) and \( \theta_7 \) also have coupling relationship, \( \theta_6 + \theta_7 = \pi \).

The coordinate system of each link is formed as shown in Fig. 5, and based on D-H method, robot link parameters are obtained. Link parameters of inspection robot are shown in Table I, specific values of link parameters are not listed. We can derive the kinematics of the mechanism by matrix multiplication of the individual link matrices:

\[
\begin{align*}
&T = \begin{bmatrix}
T_{0} & T_{1} & T_{2} & T_{3} & T_{4} & T_{5} & T_{6} & T_{7} & T_{8} & T_{9} & T_{10} & T_{11} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\end{align*}
\]

Where \( c\theta \) is shorthand for \( \cos \theta \), \( s\theta \) for \( \sin \theta \), \( c\theta_{i-j} \) for \( \cos(\theta_i - \theta_j) \), \( s\theta_{i-j} \) for \( \sin(\theta_i - \theta_j) \) and so on, \( i,j = 1,2,3 \ldots \);

\[
\begin{align*}
n_x &= c\theta_{3,5} c\theta_{10}, n_y = s\theta_{10}, n_z = -s\theta_{3,5} c\theta_{10}, \\
a_x &= -c\theta_{3,5} s\theta_{10}, a_y = c\theta_{10}, a_z = s\theta_{3,5} s\theta_{10}, \\
a_z &= s\theta_{3,5}, a_y = 0, a_z = c\theta_{3,5}, \\
p_x &= 2(c\theta_{4} - c\theta_{5}) c\theta_{11} / 5 - 7s\theta_{3} / 20 - 7c\theta_{3,5} / 40 \\
p_y &= d_2 - d_9 + 2s\theta_{3} / 5 + 2c\theta_{3} / 5 \\
p_z &= 2(c\theta_{4} - c\theta_{5}) s\theta_{11} / 5 - 7c\theta_{3} / 20 - 7c\theta_{3,5} / 40 - 7 / 40
\end{align*}
\]

| \( \phi \) | \( \alpha_{i-j} \) | \( a_{i-j} \) | \( d_{i-j} \) | \( \theta_{i-j} \) | Joint variable |
|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | \( \theta_1 \) | \( \theta_1 \) |
| 2 | 0 | \( a_1 \) | \( d_1 \) | 0 | \( d_1 \) |
| 3 | 0 | 0 | 0 | \( \theta_2 \) | \( \theta_2 \) |
| 4 | \( a_2 \) | \( a_2 \) | 0 | \( \theta_3 \) | \( \theta_3 \) |
| 5 | \( a_3 \) | 0 | \( d_3 \) | \( \theta_4 \) | \( \theta_4 \) |
| 6 | \( a_4 \) | \( a_4 \) | 0 | \( \theta_5 \) | \( \theta_5 \) |
| 7 | \( a_5 \) | 0 | 0 | \( \theta_6 \) | \( \theta_6 \) |
| 8 | \( a_6 \) | \( a_6 \) | 0 | \( \theta_7 \) | \( \theta_7 \) |
| 9 | 0 | 0 | \( a_9 \) | 0 | \( d_9 \) |
| 10 | \( a_{10} \) | \( a_{10} \) | \( \theta_{10} \) | \( \theta_{10} \) |

B. Force Analysis of Parallelogram Mechanisms

Each arm of the mechanism is a parallelogram independent mechanism. Joint 4 or 5 can play the role of active joint in the design with no difference. However, Joint 4 is the active joint in the force analysis, as shown in Fig 6. Four bar force model is shown in Fig 7.
\[ R_{l1} - R_{l1}' = 0 \]
\[ R_{l1}' + R_{l1} = G_l \]
\[ R_{l1}'' \sin \theta - R_{l1}' \cos \theta = -G_l \cos \theta l / 2 \]  
\[ R_{l2} - R_{l2}' = 0 \]
\[ R_{l2}' - R_{l3} = G' + G_2 \]
\[ R_{l2}'' l_2 + M_r = M' - (G' + G_2) l_2 / 2 \]
\[ R_{l3} - R_{l3}' = 0 \]
\[ R_{l3}' + R_{l3} = G_i \]
\[ R_{l3}'' l_3 \sin \theta - R_{l3}' l_3 \cos \theta = -G_i \cos \theta l / 2 \]

According to the above equation, the expression of the driving moment is as follow,
\[ M_r = (G_i + G_l) l_c \cos \theta - 2M \sin \theta + G_l \cos \theta + G' l_3 \theta l / (l_1 - 2l_3 \sin \theta) \]  

V. SIMULATION AND ANALYSIS

A. Obstacle Negotiation Sequence

According to the analysis of 110kV transmission line environment, jumpers represent the most challenging type of line to traverse [9, 10]. So, the process of navigating strain clamps is planned as a typical representative of obstacle navigation process. Taking a jumper obstacle as an example, the detailed descriptions of the obstacle navigation sequence are as follows.

(a) The robot stops in front of the obstacle to cross. The gripper of the fore arm clamps firmly onto the conductor from above to secure the robot.

(b) The rear arm slides forward so that the center of gravity of the mechanism is now located below the forearm. Then, the rear arm extent it is higher than the strain clamp, the rear arm rotates to move the rear locomotion mechanism away from the conductor.

(c) The rear and fore arms swing to move the rear locomotion mechanism into proximity with the jumper. The electrical box slides backward so that the center of gravity of the mechanism is still located below the fore arm. The rear arm rotates to bring the rear gripper into alignment with the jumper, and the gripper clamps onto it, providing a new set of supports for the robot.

(d) The gripper of the fore arm releases and is moved away from the conductor.

(e) The rear and fore arms swing to move the fore locomotion mechanism into proximity with the jumper.

(f) The rear arm rotates to bring the fore gripper into alignment with the jumper, and the gripper clamps onto it.
The processes of navigating strain clamp are shown in Fig. 9. The centroid must be adjusted to the attached arm which can improve stability of the navigation and decrease the deformation of jumper during the whole process.

B. Simulation

The two arms of the mechanism move from conductor to jumper one by one with same movements [11, 14]. So, the first half of this process is simulated, which can illustrate the mechanism is qualified for this task. The start and end position of the mechanism are shown in Fig. 9.

As mentioned above, taking the confined space at the strain clamp and safety and stability requirements of the navigation into account, the multi joint linkage should be avoided, each action will be driven by only one joint. According to the characteristics of the obstacle and the environment, the trajectory of the mechanism end effector is planned as shown in Fig. 10. Firstly, the mechanism end effector is moved from G1 to G2 though the joint $\theta_6$ & $\theta_7$ of the rear arm; then from G2 to G3 though the joint $\theta_8$; successively, though the joints $d_o$, $\theta_6$ & $\theta_7$, $\theta_8$, $\theta_6$ & $\theta_7$, the end effector of the mechanism arrives at G6. Then, the mechanism finishes the navigation of strain clamp. The joint velocity is planned by the function of step, as follows:

$$
\text{Step}(x, x_i, h_i, h_f) = \begin{cases} 
  h_0 & x \leq x_i \\
  h_0 + (h_f - h_0) \frac{x - x_i}{x_i - x_0} & x_i \leq x \leq x_f \\
  h_f & x \geq x_f
\end{cases}
$$

(7)

Where $x$ begins at $x_0$ and ends at $x_1$, $h_0$ represents the initial function value, $h_f$ represents the final function value.

The origin of coordinates is located in the front wheel center. The rear gripper releases and is moved away from the conductor as its first step to attaching to the jumper, then the coordinate of G2 is (-0.32, -0.04, 0). The rear arm and the front arm rotate to move the rear location mechanism into proximity with the cable, as shown in Fig. 11c, then the coordinate of G6 is (0.35, -0.33, -0.28). The rear arm joint brings the gripper into alignment with the jumper, and the gripper attaches, as shown in Fig. 11d, the coordinate of G8 is (0.38, -0.46, 0.04).

Results for the navigation of the strain clamp are shown in Fig. 11. Fig. 11(a) shows the curves of joints displacement. Fig. 11(b) shows the curves of joints velocity. Fig. 11(c) presents the end effector’s trajectory. Fig. 11(d) presents the end effector’s velocity.

To verify the correctness of the kinematics model, Matlab is used to get the forward kinematics by contrast with the results of the 3D simulation. Five special arm positions are chosen in Tab. II.

These five special arm position calculation results are shown in Table II. These results, representing the position of the end effector, are just on the trace curve in Fig 11(c), which demonstrate the correctness and effectiveness of the kinematics model.

The navigation of the strain clamp is simulated in Adams. Results of the simulation of the strain clamp navigation show the mechanism can navigate the strain clamp successfully and cross onto the jumper.
VI. CONCLUSION

The design and analysis of a novel inspection robot mechanism for power transmission lines have been presented. Its configuration is introduced, and the kinematics equations and statics model are established. The robot can move on the conductor steadily and rapidly by using a wheeled locomotion mechanism. The wheel-arm and a centroid adjustment mechanism ensure the robot has obstacles crossing ability and climbing ability. Besides, the parallelogram mechanism improves the overall stiffness, and enhances the load capacity of the robot. The simulation results prove that this mechanism can move rapidly and negotiate complicated obstacles steadily with heavy load, and is suitable for transmission line inspection.

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