International Journal of Frontiers in Engineering Technology
ISSN 2706-655X Vol.6, Issue 3: 84-89, DOI: 10.25236/IJFET.2024.060311

A Kinematic Analysis of a Line Robot Based on Biomimicry of Inchworms

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Abstract: *In this paper, an in-depth exploration is conducted on the primary methodologies currently employed for high-voltage cable inspection, alongside the inherent challenges they pose. To address these challenges head-on, a novel climbing robot is proposed, inspired by the intricate movements of inchworms. This innovative robot exhibits exceptional capabilities in swiftly navigating along cables and efficiently overcoming various obstacles encountered in its path. Utilizing advanced mathematical analysis and comprehensive simulations, the projected theoretical running speed of this robotic system is estimated to hover around 1.1 meters per second. Such a remarkable feat underscores its potential for rapid movement and remarkable adaptability, particularly within the dynamic and complex environments often encountered within the power industry.*

Keywords: *line robot, inchworm locomotion, biomimicry, Kinematic analysis*

1. Introduction

In recent years, with the continuous improvement of China's industrialization level, electricity has become an indispensable part of our lives. With the rapid development of China's cable industry and the increasing total mileage of high-voltage cable installations, the demand for cable inspection, cleaning, and maintenance is also growing. Currently, there are three main methods for high-voltage cable inspection: manual aerial inspection, drone inspection, and robot inspection. Manual inspection is the most traditional method but has many disadvantages such as high labor intensity, inaccurate judgment, and high risk. Drones also have safety hazards and inadequate navigation in high-voltage line inspections. Overall, robotic climbing inspection machines have better comprehensive performance.

Typical dual-arm robots include the Skysweeper developed by Morozovsky and Bewley, which can overcome obstacles by swinging itself.[1] However, if it carries many electronic components, it will increase weight and reduce flexibility, making it unable to cross obstacles effectively. Multi-arm robots are more widely researched at present. Due to better support, multi-arm robots are more stable than dual-arm robots and can also overcome obstacles in cables. The LineBot robot designed by the Chinese University of Hong Kong in cooperation with Chongqing Electric Power Company can move on cables through a variable-pitch joint structure with two active arms and two joints, but its speed is very slow. [2]

LineRanger developed by the Hydro-Québec Research Institute (IREQ) in Canada is currently the most powerful cable climbing robot. [3] It can quickly walk on cables, cross obstacles on cables using the cooperation of wheels and springs. However, it cannot cross towers, and its weight is large, still having some shortcomings.

For inspection methods such as drones or flying climbing, there are corresponding researches currently. Drone inspection is not affected by obstacles on the cable itself, and LineDrone is the most advanced robot in this regard, capable of detecting circuit corrosion and many other functions. [4-5] However, there are still challenges in mass production and how to stably grip the power line, leaving room for further development.

This device mainly adopts the structure of bionic caterpillar movement. When the caterpillar moves, the front four legs hold while the rear four legs open, pulling the rear half of the body forward by curling up the body, then alternately making the rear four legs hold while the front four legs open, pushing the front half of the body forward by stretching the body.

Although the caterpillar has both "extension" and "contraction" movements during its movement, its movement is always forward, and caterpillars often move on poles and stems, which is similar to the movement of inspection robots on cables. At the same time, the caterpillar's multi-leg gripping force is strong, which can effectively fix it on stems and also cross adjacent stems, showing high flexibility. This device fully absorbs the advantages of the caterpillar's structure, enabling fast movement on cables and crossing obstacles, providing significant advantages in scenarios involving long-distance transmission cables.

2. Motion Program Design

During the movement process, this device is based on a "bow" shape (as shown in Figure 1). Initially, the device's rear grip closes to hold the wire while the front grip releases. With the torque output from the driving motor, the gear linkage mechanism is activated, and under a certain gravity, the device slides forward until it approaches a "I" shape, at which point the motor stops running. Subsequently, the front grip closes to hold the wire while the rear grip releases, and the motor continues to run, lifting the rear part of the device, returning to the "bow" shape. This process constitutes one movement cycle. Through multiple such cycles, the device crawls and overcomes obstacles on the wire.

The climbing drive module is mainly driven by a servo motor rotating the gear shaft, achieving direction reversal through bevel gears. The main shaft is connected to the bevel gears and has a gear at the end to transmit the motion of the device. The small gear is the driving wheel, rotating the large gear, which in turn drives the linkage motion.

By transmitting in this way, the angle between the middle and ends of the robot can be changed. Additionally, there are electric push rod structures on both sides of the climbing mechanism of the device, used to extend and retract the grippers to enhance the practicality and versatility of the device. Moreover, in the climbing mechanism, by changing the tightening and loosening sequence of these two claws, relying on the wide grippers of the inner two claws, it can effectively mimic the movement structure of the inchworm's front and rear ends, achieving a biomimetic crawling effect.

When the device encounters obstacles such as insulator strings or vibration dampers, the obstacle avoidance function is activated. During obstacle avoidance, the device identifies the obstacle's position, adjusts the gripper structure by rotation using its own structural characteristics, and the grippers release and grip at appropriate times to overcome obstacles on the wire pole.

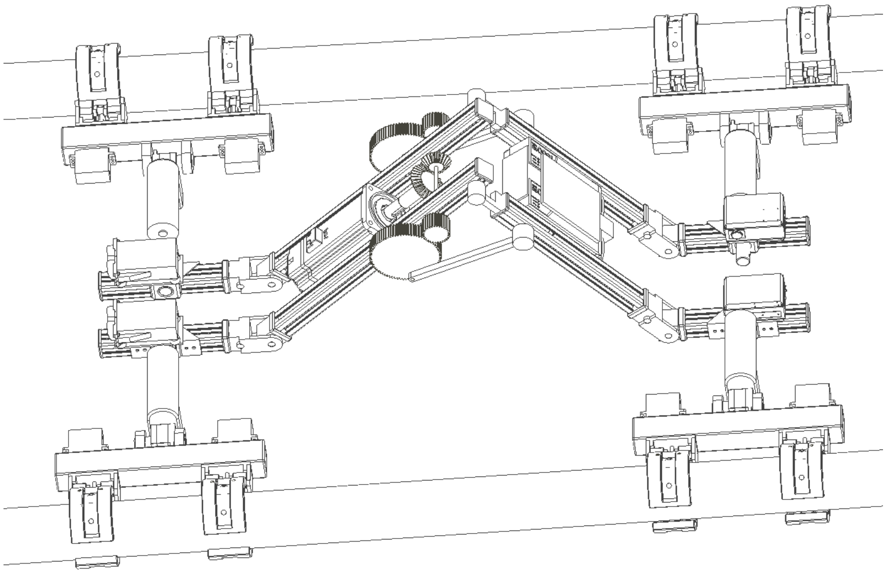

Figure 1: Device schematic.

The broad application of the rotary kilns in a variety of industrial branches for thermal processing of residual materials with a different origin and mostly for fire treatment of hazardous wastes [2-3]. The rotary kilns were used as rotary dryer to remove moisture and water from solid substances, primarily by introducing hot gases into a cylinder, it acts as a conveying device and stirrer.

3. Kinematics Model Analysis

3.1. Model Building

The motion mechanism is represented by a slider-crank model, as shown in Figures 1 and 2. The driving gear acts as the input rod of the crank mechanism, driving the transmission rod, which in turn drives other rods. Figure n depicts the model of the device moving forward, with the driving gear positioned above the horizontal line. The front grip can be considered a rocker, and the rear grip as a fixed end. Figure 3 represents the model where the rear part of the device is pulled, with the front grip and rear grip in a mirrored state. At this point, the driving gear is positioned below the horizontal line.

When the device's driving gear is at the horizontal line and moving downward (clockwise rotation), the front grip remains fixed while the rear grip acts as a slider. The driving gear drives the transmission rod, which in turn drives the rear rod, causing the rear grip to slide forward and return to its position. As the driving gear returns to the horizontal line, the rear grip becomes fixed while the front grip acts as a slider, resulting in the minimum angle of the device. Continuing clockwise rotation of the driving gear then drives the front rod, causing the front grip to slide forward and enabling the device to move forward.

3.2. Thermal Processing

When the device moves forward, the angle changes from θmin to θmax, indicating the motion state when the front arm driving gear rotates clockwise, as shown in Figure 2. Let the length of the front rod be b, the length at the connection with the driving rod be a, the equivalent rod length of the driving gear be z, the length of the transmission rod be y, and the distance traveled by the front rod be x.

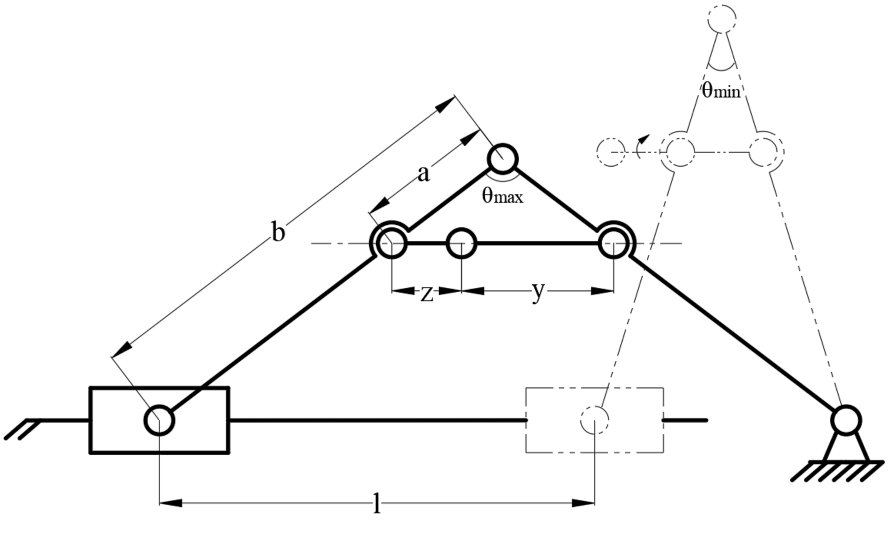

Figure 2: Kinematic Sketch of Forearm Motion Mechanism

When the device is at θmin, from the geometric relationships, it can be inferred that:

$$\mathrm{Sin}(\theta_{min}/2)=((y-z)/2)/a \tag{1}$$

When the device is at θmax, from the geometric relationships, it can be inferred that:

$$\mathrm{Sin}(\theta max/2)=((y+z)/2)/a \tag{2}$$

From this, it can be determined that when the driving gear rotates half a turn, the forward distance of the front grip of this device is:

$$l=2b[\sin(\theta_{max}/2)-\sin(\theta_{min}/2)] \tag{3}$$

Simplified, it can be concluded that:

$$l=2bz/a \tag{4}$$

Therefore, the motion speed of the front arm of the device is only related to the total length of the front arm, the distance from the front arm to the fixed point of the driving gear, and the length of the transmission rod. Therefore, to increase the motion speed of the device, one can increase the length of the front arm, the equivalent length of the driving gear, and reduce the distance from the front arm to the driving gear.

Since the mechanism needs to satisfy the basic conditions of link motion, according to the conditions of triangle side lengths, when it is at the maximum angle:

$$a+a>y+z \tag{5}$$

When it is at the minimum angle:

$$y-z>0 \tag{6}$$

$$a>z \tag{7}$$

Therefore, if we take $z = 0.9a$ and $y = a$, we can obtain that the forward distance each time is $l = 1.8b$.

When the driving gear rotates below the horizontal line, the device enters the state of retracting the rear arm. Its motion state is shown in Figure 3, where the retraction distance of the rear arm is the same as that of the front arm, and during this period, no power is provided for forward movement, so further analysis is not conducted.

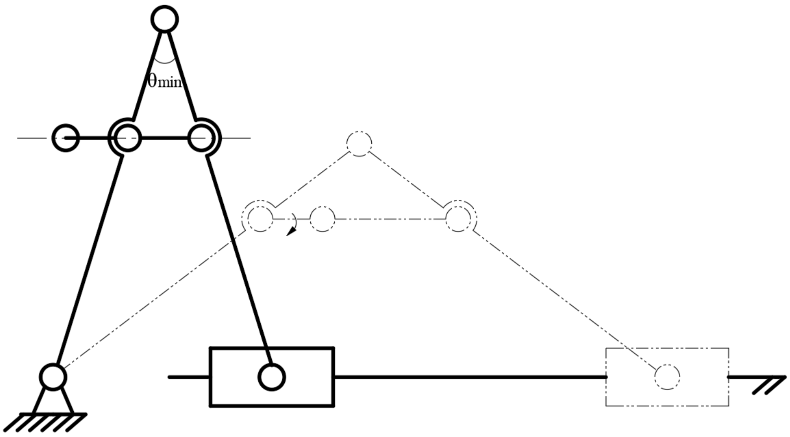

Figure 3: Kinematic Sketch of Rear Arm Motion Mechanism

3.3. Motion Simulation

Based on the actual situation, in this motion simulation, taking b = 500mm, a = 80mm, x = 80mm, y = 72mm, the theoretical forward distance each time is 900mm.

The initial position is as shown in Fig. 4. Apply a counterclockwise rotation speed of 120 rpm to the driving gear, rotate it 180 degrees, pause briefly, release and re-grip the claws, then continue rotating the driving gear.

Figure 4: The initial state of the device

Fig. 5, Fig. 6 and Fig. 7 show the motion states of key positions during the movement:

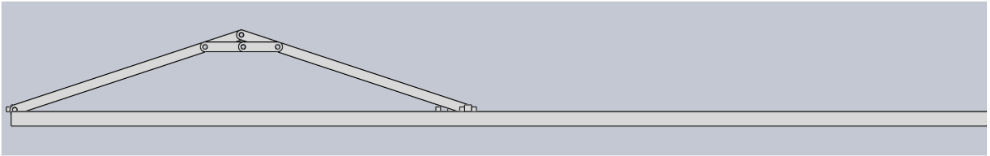

Figure 5: The forearm in the extended state

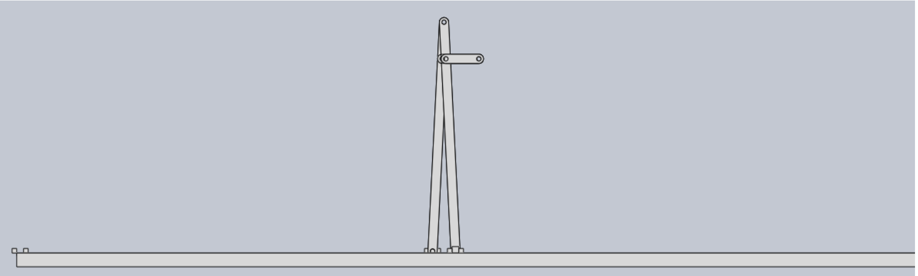

Figure 6: Rear arm recovery status

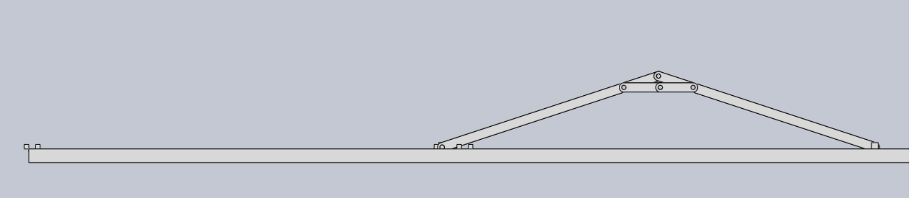

Figure 7: The forearm in the extended state again

The motor is driven in a cubic form, and its angular velocity relative to time is simulated as shown in Fig. 8:

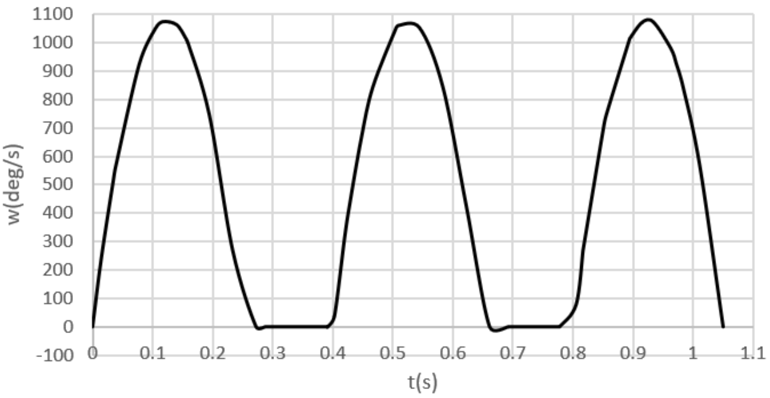

Figure 8: Phase analysis of arrangement

The resulting simulation curve of the displacement of the front end of the device relative to time is shown in Fig. 9:

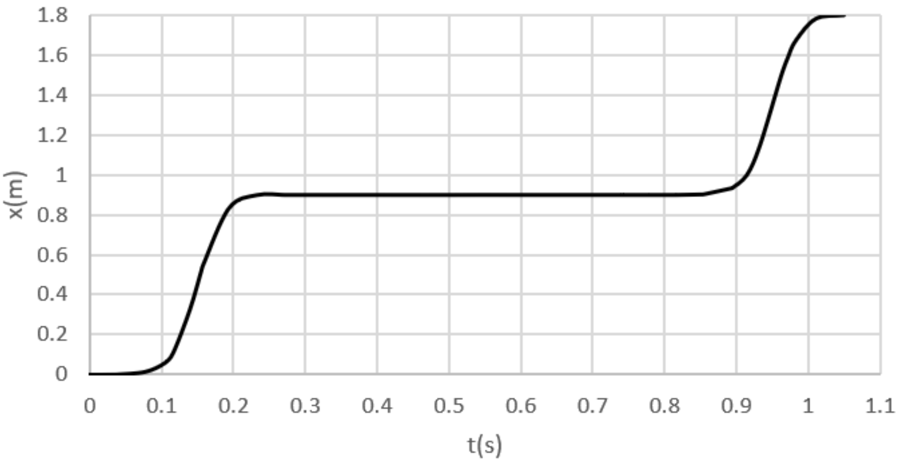

Figure 9: Phase analysis of arrangement

From this, it can be concluded that under the conditions set, the theoretical forward speed of the device is 1.125 m/s.

4. Conclusion

Drawing inspiration from the motion posture of an inchworm, a robot adaptable to cable walking was designed. This paper mainly analyzes its motion principle and mode.

Through mathematical analysis, calculation, and motion simulation, the theoretical operational speed of the crawler is determined to be approximately 1.1 m/s. With a fast motion speed and the ability to adapt to complex cable environments, it holds great potential for application prospects.

Acknowledgements

This paper was supported by National innovation and entrepreneurship training program for college students S202310497140.

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