Analysis of load variation of two-pipe climbing robot under three gait conditions

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Abstract. This paper presents a double-piped climbing robot, which is designed for the detection and maintenance of boiler pipes in coal-fired power plants. It studies the three gaits of climbing robots: crawl, reversal and torsion. This research has established a virtual prototype of the climbing robot. By using the simulation software, ADAMS, we analyze the clamping force of the robot’s mechanical arm, and also the changing conditions of the key motor’s torque during the climbing process. Analysis the robot in the quality of external load change influence on robot driving moment, the result can be extended as a robot uses, optimize the robot structure as the basis, to ensure the stability and security of climbing performance.

1. Introduction
At present, the cleaning and testing of boiler pipelines in domestic coal-fired power stations are mainly undertaken by manual workers. The conventional method is to stop the furnace maintenance, put up scaffolding in the furnace, first by artificial visual measurement to judge the appearance of abnormal pipe wall, and then use the hand-held ultrasonic flaw detector to measure the area pipe wall one by one, and then replace the damaged pipe. The main disadvantages of traditional methods are: long working cycle, low working efficiency; Poor reliability, manual judgment and incomplete testing, the pipeline exist defects and misjudgment; The difficulty of boiler pipeline detection in domestic coal power stations is that the space is 8-15 meters high and there are obstacles on the pipeline. High detection cost, prone to accidents, detection workers working at height, poor safety. Therefore, if the aerial pipeline inspection robot[1-3] is adopted to replace manual operation, the work efficiency, maintenance reliability and operation safety can be greatly improved.

Faced with these demands, boiler inspection robot with climbing function is increasingly studied by domestic and foreign scholars, and a large number of prototype pipeline climbing robots have been developed. These robots can be roughly divided into permanent magnet adsorption climbing robot and clamping robot. Harbin Institute of Technology has developed a permanent magnet adsorption wall-climbing robot[4], and ChangZhou university has developed a boiler water-cooling wall-wear detection robot[5]. The advantages of this kind of climbing robot are that its adsorption ability is relatively stable. Permanent magnet adsorption blocks are installed on the track and wheels, which have good contact with the wall surface and even force distribution. However, the disadvantage is the lack of the ability to climb and climb obstacles, so the application is limited to the pipeline without obstacles. South China university of technology has developed a two-handed claw robot [6], and Mahmoud Tavakoli of Portugal has developed a climbing robot named 3D Climber[7]. All of them adopt single-pipe clamped type, but their disadvantages are poor stable performance of climbing on the pipe, insufficient bearing capacity, and easy to fall.

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2. The gait principle of two-pipe climbing robot

Through the kinematics analysis of the dual-pipe climbing robot through the simulation software, three climbing gait modes were summarized, the maximum joint torque required by different gait modes and the power consumed were calculated and compared, which could guide the movement planning of the robot between the pipelines, compare the energy consumption, and plan the optimal climbing path [8].

Figure 1. The schematic diagram of joint structure.

2.1. Crawling gait

Autonomous climbing when no obstructions, gripper G1 piping fixed, gripper G2 loosen pipeline peristalsis is supreme, to clamp the pipe, the gripper G1 and obstacles are close, also can also autonomous navigation when encountered obstacles, gripper G1 built-in sensors detect the exact location of obstruction to take peristalsis gait as shown in figure 5, gripper G2 to loosen, joints, T1, T2, T3, T4 and joint work, can make the robot slowly rising a little lift L1, ready to cross the barrier, if we do not plan to climb the path,The G2 gripper of the manipulator will encounter obstacles in the process of overturning, resulting in the inability to normally pass.

Figure 2. Schematic diagram of Crawling gait.

The purpose of adopting Crawling gait is to adjust the posture, control the reasonable distance between the gripper G1 and the obstacle, and maintain a reasonable distance to ensure that the climbing robot can successfully cross the obstacle and climb up to L1 in the next movement.
2.2. Reversal gait

When the height of obstacle is larger than 40cm, the reversal gait is adopted to cross it.

(1) The reversal gait as shown in figure 3, state 1 for climbing robot encountered obstacles in the lift of the initial position, gripper G1 built-in sensors detect the obstacles of distance and automatic adjusting posture, control the reasonable distance of the gripper G1 and obstacles remain reasonable distance to ensure 2 obstacles smoothly, ensure the gripper G1 clamping the location of the joints T1, T2, T3, T4 trunk between the total length is greater than the width of the barrier. After the gripper G1 determines the position and holds the pipe, it first controls the release of the gripper G2, then controls the joint T1 to rotate clockwise by 15 degrees, and T2 to rotate clockwise by 45 degrees to reach the state 2 position.

(2) At state 2, the gripper G2 has been separated from the pipe, and the steering joint T1 rotates 90° clockwise, joint T3 rotates 15° clockwise, and T4 rotates 100° clockwise to reach state 3.

(3) State 3 indicates that the whole climbing robot has Reversal over to the upper position, and the gripper G2 has Reversal over to the top of the pipe. The steering joint T1 has rotated clockwise by 30 degrees, and the joint T2 has rotated clockwise by 30 degrees to reach state 4. Finally, the gripper G2 has been controlled to clamp the pipe and complete the climbing action.

2.3. Reversal gait

When the height of obstacle is smaller than 40cm, the reverse gait or the torsion gait can be adopted.

(1) The torsion gait is adopted as shown in figure 4. State 1 is the initial position of gripper G1 of the climbing robot to keep a reasonable distance from the obstacle. After the gripper G1 holds the pipe, it first controls the release of the gripper G2, and then controls the joint T1 to rotate clockwise 60 degrees to reach the state of 2.

(2) In state 2, the gripper G2 has been separated from the pipe, and the steering joint K1 is rotated 180 degrees vertically to the inside of the paper to reach state 3.
(3) State 3 is the state when the climbing robot twists up, and then controls joint T1 to rotate clockwise by 30 degrees until it reaches state 4 to complete the climbing action, at which the climbing length is L3.

Table 1. Three main characteristics of gait.

| Climb gait | Crawling gait | Reversal gait | Torsion gait |
|------------|---------------|---------------|--------------|
| Main joints | T4            | T4            | K1           |
| Climb length | L1=20cm       | L2=20−40cm   | L3=40cm      |
| Obstacle ability | NO         | GOOD          | GOOD         |
| Holding order | NO          | Alternate     | Alternate    |

It can be seen from table 1 that in the analysis of the main characteristics of three different gait, the best obstacle climbing ability is the reverse gait, and the largest climbing length in a gait is the reverse gait and the reverse gait.

3. Climbing simulation analysis

3.1. Analysis of influence of load change on driving torque

An important use of climbing detection robot is to install corresponding tools, detection device and camera device on the body of the robot. The expansion of such functions will change the structural parameters of the robot. Therefore, the influence of the change of the external load mass of the robot on the driving force torque performance is discussed.

(1) External load mass increased by 1.0kg

When designing the climbing robot, the maximum load that the robot can carry is 1.6kg. When the robot only needs to carry the camera device, the external load should be controlled within 1.0kg. Three kinds of motion gait analysis were carried out under ADAMS for simulation analysis to obtain the driving torque of main joints, As shown in figure 5-7. When the external load mass increased by 0Kg, the maximum value of the Crawling gait joint T4 was 1812N.m. The maximum value of T4 in the Reversal gait is -4112N.m, and the maximum value in the twisted gait K1 is -1294N.m. When the mass of external load increased by 1.0kg, the initial value of joint T4 in Crawling gait increased from 1892N.m to 2593N.m, and the maximum value increased by 781N.m compared with that without load. The initial value of joint T4 changed from 2124N.m to -5531N.m in the Reversal gait, and the maximum value increased by 1419N.m compared with the case without load. The initial value of joint K1 changed from 2330N.m to -2031N.m under torsional gait, and the maximum value increased by 736N.m compared with the case without load. It can be seen that when the external load mass increases by 1.0kg, the maximum change value of T4 in the Reversal gait is achieved.

(2) External load mass increased by 1.5kg

Since the maximum load that the designed robot can carry is 1.6kg, the added mass of the external load cannot exceed 1.6kg, and the added mass selected in the simulation is 1.5kg. Since the robot needs to carry both the camera and the detection device, the external load should be controlled within 1.5kg. Similarly, three kinds of motion gait analysis were carried out under ADAMS for simulation analysis to obtain the driving torque of main joints. As shown in figure 5-7, when the mass of external load increased by 1.5kg, the initial value of joint T4 in Crawling gait increased from 2756N.m to 4230N.m. The initial value of joint T4 changed from 2124N.m to -7028N.m in the Reversal gait, and the maximum value increased by 2919N.m compared with the case without load. The initial value of joint K1 changed from 2330N.m to -2031N.m under torsional gait, and the maximum value increased by 1336N.m compared with the case without load. It can be seen that when the external load mass increases by 1.5kg, the change of T4 of the joint in the Reversal gait is the largest.
3.2. Simulation result

Figure 5. The torque of the main joint motor T4 in crawling gait.

Figure 6. The torque of the main joint motor T4 in reversal gait.

Figure 7. The torque of the main joint motor K1 in torsion gait.

Table 2. Torque and energy consumption of main joints when external load is 0kg

|                  | Climb gait | Crawling gait | Reversal gait | Torsion gait |
|------------------|------------|--------------|---------------|-------------|
| Main joints      | T4         | T4           | T4            | K1          |
| Maximum torque (N.mm) | 1812       | -4112        | 1294          |             |
| Maximum power (W) | 6.1        | 7.2          | 5.1           |             |
| Energy consumption (J) | 78.8       | 45.6         | 42.6          |             |
Table 3. Torque and energy consumption of main joints when external load is 1.0kg

| Climb gait | Crawling gait | Reversal gait | Torsion gait |
|------------|---------------|---------------|--------------|
| Main joints | T4            | T4            | K1           |
| Maximum torque (N.mm) | 2593          | -5531         | 2330         |
| Maximum power (W)     | 7.2           | 9.2           | 6.5          |
| Energy consumption (J) | 88.6          | 105.6         | 72.6         |

Table 4. Torque and energy consumption of main joints when external load is 1.5kg

| Climb gait | Crawling gait | Reversal gait | Torsion gait |
|------------|---------------|---------------|--------------|
| Main joints | T4            | T4            | K1           |
| Maximum torque (N.mm) | 4230          | -7028         | 2536         |
| Maximum power (W)     | 8.9           | 11.2          | 6.9          |
| Energy consumption (J) | 78.6          | 145.9         | 42.2         |

As can be seen from table 2,3,4, the torque and energy consumption of the main joints in three different gait modes are as follows: the torque of the most required gait is torsion gait; the maximum power occurs in the Reversal gait; the energy consumption of the least required gait is torsion gait. In consideration of saving as much as possible and reducing power consumption in climbing, the motor torque and power consumption of main joints in different gait states can be analyzed through simulation and experimental prototype, which can guide the optimization of motion path and reduce the loss of energy consumption[10].

According to the analysis of simulation results and experimental measured data, we can install different devices on the climbing robot according to the driving power of the selected motor, namely the parameters, to determine whether the current power can meet the requirements.

3.3. Experimental prototype construction

As shown in figure 8, the experimental prototype was built, which was composed of manipulator gripper G1, G2, steering joint K1, K2, joint motor T1, T2, T3 and T4. The selection of key motors of the robot was completed through simulation data[10].

Figure 8. Experimental prototype.
4. Conclusion

(1) A new type of boiler dual-pipe climbing robot is designed. The robot adopts the method of clamping two pipes, and the manipulator can bear the load of the body during climbing, so as to ensure the stable walking of the robot.

(2) The simulation data and experimental data provide some guidance for the improvement of the following experimental prototype.

(3) Through the analysis of the driving torque of each major joint when the load mass of the robot changes, it can be used as an important basis for the robot to carry different tool modules and select the driving motor of the climbing robot. It can also further optimize the structure of the climbing robot and improve the load carrying capacity of the robot.

Autonomous identification of pipeline defects and detection and analysis will be added to the robot in the future.

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