Design and Implementation of Four-link Robot Crawler with Variable Structure

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Abstract. A kind of crawler-type robot with variable structure based on four-bar linkage was designed to solve the obstacle clearance problem. Firstly, the design scheme of the variable structure tracked robot was proposed, and the virtual prototype was designed. Then the mathematical model between the deformation of the four-bar linkage and the total length of the track was established. the numerical analysis shows that the total length of the track is 0.91% in the deformation process, which is smaller than the elongation of the general rubber track. The feasibility of the scheme was verified theoretically. Finally, a physical prototype experiments were carried out and experiments show that the variable structure crawler could achieve good obstacle performance through deformation.

1. Introduction

In recent years, small variable-structured crawler robots have been playing an increasingly important role in the search for holes and tunnels, inside buildings, and the detection and removal of anti-personnel landmines and other operations. This has aroused the attention of all countries in the world. The company of Inuktun in U.S. has developed a variable structure crawler-type reconnaissance robot (VGTV) [1-3], which can achieve the effect of simultaneous deformation of the crawler during the course of its movement. When the robot body is relatively flat, the robot is in the form of a tank; the relative change in the position of the main driven wheel can make the crawler become a triangular shape, this feature greatly enhances the robot's environmental adaptability and obstacle-obstacle ability. The "Ling-B" explosives robot developed by Shenyang Institute of Automation, Chinese Academy of Sciences, adopts a compound mobile mechanism of wheels, legs, and crawlers [4]. It has made great progress in the research of variable structure robots, but in terms of performance and reliability, compared with similar foreign robots, there is still a certain gap. Based on the deformation principle of the four-bar linkage mechanism, this paper proposes and designs a new type of variable structure double tracked robot. Its related properties and characteristics are systematically studied and in-depth discussions, and the virtual prototype design and the physical prototype movement and implementation are carried out.

2. Structural design

As shown in figure 1, for the track structure with no change in tension, the distance L between the two wheels and the length A of the main arm is a fixed value. The axis of the main arm is located at the

center point of the connecting line between the two wheels. Assume that the radius R of the wheel and the leading wheel; the angle α between the center line of the main arm and the two wheels and the main arm.

The track perimeter C can be expressed as follows while 0°≤α≤90°:

$$C = L + 2\pi R + \sqrt{A^2 + (\frac{L}{2})^2 - 2ALCOS(\alpha)} + \sqrt{A^2 + (\frac{L}{2})^2 + 2ALCOS(\alpha)} \tag{1}$$

From the analysis of formula (1), it can be seen that C increases with α. However, when the rate of change of C exceeds 5%. When the main arm is lifted, the tensioned track will break and when the main arm falls, the tensioned track begins to fall off. This structure results in a limited range of motion of the main arm and affects the crawler robot function.

To solve the above problem, a four-bar linkage mechanism is used to replace the rigid structure between the connecting rod and the wheel. As shown in figure 2, the four-link variable structure double tracked robot is mainly deformed by a robot body and two symmetrically distributed crawler belts. Device composition. The crawler deformation device is composed of a link mechanism and a swing arm. The track rod end is equipped with a track roller near the ground, and the rear wheel is a passive wheel.
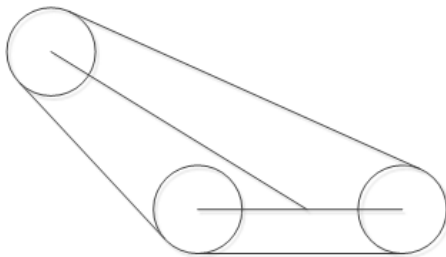
Figure 1. Unchanged track structure without tension.
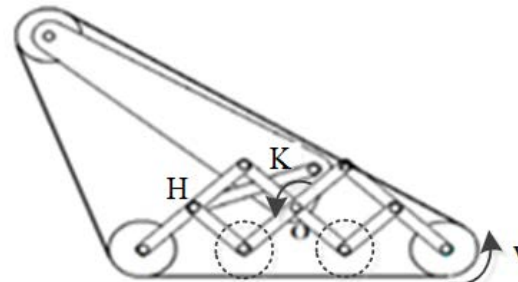
**Figure 2.** Four-link variable structure crawler structure.

The mechanism adopts a special elastic tension device. When the swing arm is raised and lowered, the swing arm drives the connecting rod HK to pull or push the rotation point O of the four-bar linkage mechanism. Because the track roller is installed at the end of the connecting rod, the main arm swings can be driven four times. The link mechanism zooms to drive the change in distance between the track rollers. While changing the structure, the lengths of crawlers on all sides are changed in real time, and the total track length of the mechanism can be kept constant by the relationship between the lengths of each link.

The advantage of the four-link variable structure double tracked robot is to fully utilize the characteristics of the four-bar linkage mechanism, and one original mover can realize the deformation of the entire mechanism. The structure of this mechanism is simple, and it is convenient to adapt to the relatively complicated working environment such as low clearance through miniaturization. In addition, the robot has good obstacle avoidance and mobility. And connect the rotary joint to zoom in the main arm and linkage mechanism. When the main boom is lifted and rotates around the center of rotation, the four-bar linkage mechanism is also shortened accordingly, which means that L is reduced to accommodate constant-length C.

3. Theoretical analysis of structural design

The main structural principle of the variable structure double tracked robot is shown in figure 3, KD rod, ED rod, and EC rod belong to the swing arm portion, so their relative positional relationship is always the same. The movement of the KD rod of the active part causes a change in the quadrilateral KDMH, which ultimately results in a change in the distance between the track rollers A, M, N, B. From the three states below, the effect of changes in AB pitch on the track perimeter C is analyzed [5].

3.1. Flat state
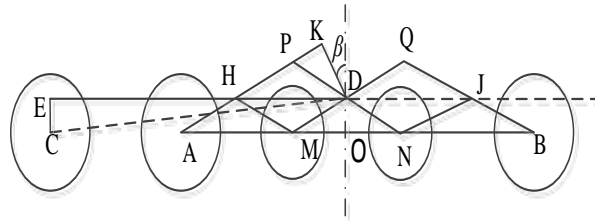
Figure 3. Schematic diagram of the flat state of the robot.

As shown in figure 3, when the ED and the HD coincide with each other, the crawler robot is in a flat state with the lowest height. The theoretical length of the crawler belt is calculated as follows:

In the quadrilateral MDKH, set the angle between the KD and the vertical center line to be β, the length of the HM and the MD equal and known, HK and ED lengths are known, the radius of the track wheel is d, and the coordinate at the K point is D The point is the relative coordinates of the origin. Then, the tangent of the included angle β is equal to the ratio of the abscissa to the ordinate of the K point, which is obtained from the triangular trilateral theorem:

$$COS(\frac{\pi}{2} - \beta) = \frac{HD^2 + KD^2 - HK^2}{2 \times KD \times HD} \tag{2}$$
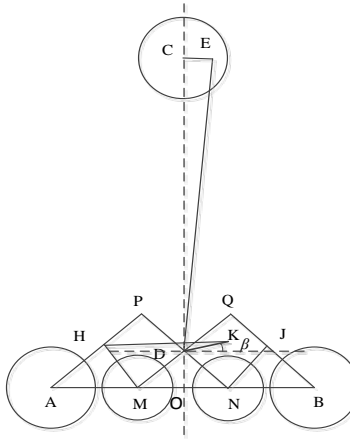
$$C = L + 2\pi R + \sqrt{A^2 + (L/2)^2 - 2ALCOS(\alpha)} + \sqrt{A^2 + (L/2)^2 + 2ALCOS(\alpha)} \tag{3}$$

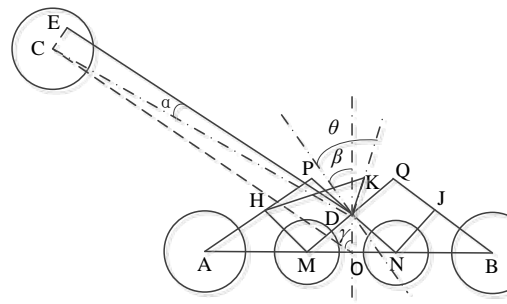Thus calculate the length of the HD. Therefore, the theoretical track length is:

$$C(0) = 2 \times \left(ED + 3 \times \frac{HD}{2} \right) + \pi \times d \tag{4}$$

3.2 When the robot is deformed to the maximum
As shown in figure 4 when the height of the robot is the highest, the length of the crawler contact with the ground is the shortest.

Figure 4. schematic diagram of the robot's highest state.

Figure 5. Schematic diagram of the general state.

Let the angle between the ED and the vertical center line be α. As can be seen from figure 3, CE and ED are perpendicular, so the tangent of α angle is equal to the ratio of CE and ED. Because HD and HK are set to known values, the expression of HD is derived from the triangular trilateral theorem formula:

$$COS(\pi - \beta + \alpha) = \frac{HD^2 + KD^2 - HK^2}{2 \times KD \times HD} \tag{5}$$

Let the vertical height between point D and AB be h, then h can be represented by HD and DM as:

$$h = \sqrt{DM^2 - (HD/2)^2} \tag{6}$$

From this we can find the length of the AC:

$$AC = \sqrt{(3 \times HD/2)^2 + (DC + h)^2} \tag{7}$$

The figure shows that AC and BC are equal. So when the height of the variable structure double tracked robot reaches the highest point, the theoretical track length is:

$$C(90) = AB + BC + AC + \pi \times d \tag{8}$$

3.3 General deformation

Figure 5 shows the relationship between the theoretical track length and the DK linkage rotation angle under normal conditions.

Assume that the angle at which the connecting rod DK turns to the normal position when starting from the initial flat state is θ. Then, the relationship between rod KD and angle θ in ΔHDK is:

$$COS(\pi/2 - \beta + \theta) = \frac{HD^2 + KD^2 - HK^2}{2 \times KD \times HD} \tag{9}$$

The angle between CO and the vertical plane is γ, which is known from the cosine law in △COD:

$$COS\gamma = \frac{CO^2 + DO^2 - DC^2}{2CO \cdot DO} \tag{10}$$

Known by △AOC and △BOC:

$$CO^2 + AO^2 + 2AO \cdot CO \cdot COS(\frac{\pi}{2} - \gamma) = AC^2 \tag{11}$$

$$CO^2 + BO^2 + 2BO \cdot CO \cdot COS(\frac{\pi}{2} + \gamma) = BC^2 \tag{12}$$

Therefore, the total theoretical track length obtained is:

$$C(\theta) = AB + BC + AC + \pi \times d \tag{13}$$

Using MATLAB software, in a number of computational experiments, it was found that the position of the K-point was the main factor affecting the deformation of the robot. Referring to figure 3, when the ratio of the abscissa and the ordinate at the K-point was 0.26 with the D-point as the origin, the structure Track length change rate is less than 1%.

In order to adapt to the working environment with a small gap and to increase the obstacle avoidance capacity, the length of the KD rod is 27.9 mm in accordance with the above formula and the simulation of the ratio of the abscissa 7 and the ordinate 27 in the software to the K point. The rod isometric rod is 80mm; the HM and other short rods are 40mm; the HK rod length is 72mm; the DE length is 200mm; the CE length is 15mm; the track wheel diameter d is 50mm.

The initial length is taken in equation (2) when the variable structure robot is in a flat state.

$$HD = 73.7\text{mm}$$

Bring the HD length into equation (4), the theoretical track length is:

$$C(0) = 778.3\text{mm}$$

When the initial length is brought into the maximum height of the variable structure double tracked robot, equation (5) is used to obtain HD=44.4 mm. The length of the theoretical track is calculated by taking the HD length into equation (7):

$$C(90) = 775.4\text{mm}$$

Bring the initial value to the relationship between the theoretical track length and the DK link rotation angle θ in general formulas (9~13). Calculated by MATLAB software and obtained when the θ∈ (0°~ 90°), the length of the theoretical crawler in the process of the lifting rod rotation in the range of 772mm ~ 779mm, so the rate of change is:

$$\eta = \frac{779 - 772}{779} = 0.91\% \tag{14}$$

Query data found that the general rubber crawler elongation is less than 4%, so the above formula calculates that η is less than 1% meets the requirements, the same track can adapt to changes in the shape of the triangle, thus enabling the robot to adapt to different geographical environment through structural changes.

4.Prototypes and experiments

The robot is virtually assembled in 3D modeling software. The rear cover assembly, the bottom frame assembly and the front cover assembly are assembled to obtain the overall assembly of the variable structure double tracked robot. The rear wheel of the robot is a driving wheel. Through the rotation of the rear wheel, the movement of the crawler is driven to realize the back and forth movement of the robot. By controlling the unilateral motor, the robot turns. In a flat environment, the robot can travel in the flattest manner, as shown in figure 6(a).

When a special variable-structure crawler robot encounters obstacles such as bosses, stairs, and trenches under relatively harsh working conditions [6-7]. By controlling the swing arm motor located in the middle part of the robot, the swing arm motor rotates, and the front cover of the robot is rotated by the gear transmission. Since the connecting rod is connected to the front cover, the rotation of the front cover drives the movement of the connecting rod and realizes four movements. Deformation of the linkage mechanism, thus achieving the deformation of the overall robot. As shown in figure 6(b):

The front cover of the robot swings upwards, and the four-bar linkage shrinks, so that the caterpillar shape is triangular, which creates an angle of attack between the front crawler of the robot and the ground. It can greatly improve the variable structure double track when it meets the environment of the boss and ravine. Obstacle ability of the robot [8]. Figure 6(c) shows the state when the robot has the largest angle of attack:

(a) The flat state   (b) The general state   (c) The highest state
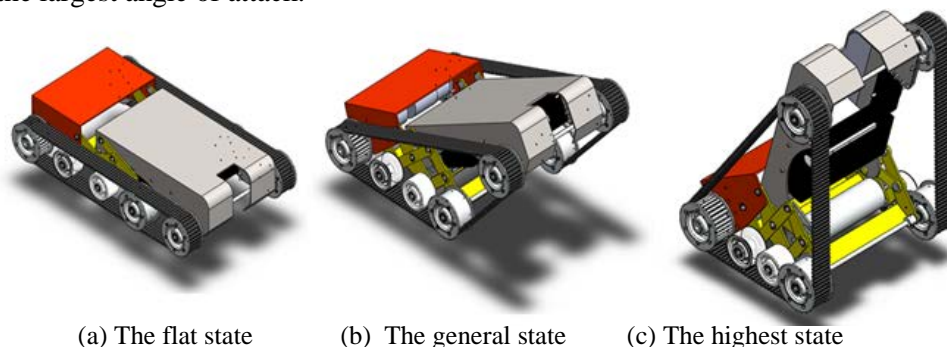
Figure 6. Virtual Prototype Model.

The assembly of the physical prototype of the four-link variable structure double tracked robot is shown in figure 7, where 7(a) is the state when the robot is flat, and figure 7(b) is the state when the front wheel of the robot is raised to form a large angle of attack.

(a) The flat state   (b) The general state
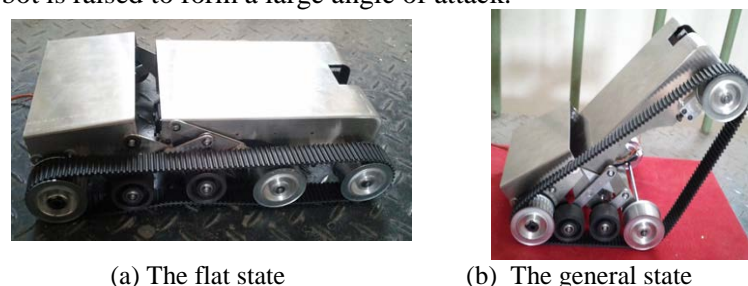
Figure 7. Physical prototype.

The test of the variable structure double tracked robot over the boss is shown in figure 8. where 8(a) shows the state of the robot on the ground. At this point, the contact area of the robot's track with the ground is the largest. When the front side encounters the boss, the robot drives the crawler by swinging the front cover of the robot through the swing arm motor, so that the track forms an angle of

attack as shown in figure 8(b). At the same time, the rear drive wheel of the robot rotates, causing the robot to move forward and climb onto the boss. After the upper boss deforms the robot to its initial position, as shown in figure 8(c). After the robot moves, the center of gravity of the robot passes through the edge. Under the pulling of gravity, the robot moves smoothly down the boss and finally passes through the boss. As shown in figure 8(d).

| (a) State1 | (b) State2 | (c) State3 | (d) State4 |
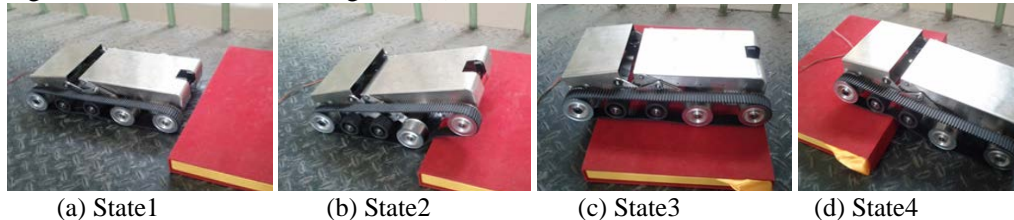
Figure 8. Overbore Experiment.

Experiments show that the tracked robot can achieve the task of overturning the boss by actively adjusting the angle of attack of the track. The four-link zoom mechanism can ensure that the track of the robot stays in a tensioned state without slackening and slipping by adjusting the track wheel spacing.

5. Conclusion

This paper proposes a design method of a four-bar linkage variable structure double tracked robot. Taking the four-link double tracked robot as the research object, a mathematical model is established between the deformation of the four-bar linkage and the change of the meshing length of the track section. The rationality of the scheme was verified from both theoretical calculations and experimental verifications. Through analysis, the following conclusions can be drawn:(1) The robot can actively adjust the pitch of the angle of attack and the track wheel through the linkage zoom mechanism, which effectively ensures the ability of the robot to adapt to the terrain by changing the structure.(2) In the process of adapting the deformation of the zoom mechanism to the terrain, there is no detachment or relaxation of the track and track wheels, and the tension is maintained at all times, which proves the scientific rationality of the proposed mathematical model. The track length deformation is less than 1%, which can greatly improve the tracked robot's obstacle performance.

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