Passive Adaptive Robot Obstacle Analysis and Optimization

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Abstract. In order to improve the obstacle performance of robots in complex terrain environment, a crawler passive adaptive robot is proposed, which is mainly composed of car body module and track module. The link mechanism of the track module has a degree of freedom, and the carbon fiber material has the characteristics of light weight and high rigidity. The obstacle course of the crawler module is introduced, and the mathematical model is established. The obstacle obstacle ability is analyzed. On this basis, the optimization parameters and the objective function are proposed. The rod length parameters of the linkage mechanism are optimized by matlab. The analysis and simulation motion analysis of the optimized linkage mechanism verify the rationality of the obstacle performance and structural parameter design of the robot.

1. Introduction
In unstructured terrain such as dangerous disasters and earthquakes, mobile robots are required to have good barrier performance, terrain adaptability and operability. Research on passive adaptive robots, including wheeled robots including Micro5 robots [1], guided rods for walking obstacles [2], triangular linkage detonation robots [3], etc.; crawler robots can be divided into three types. They are single-section double track type, double section double track type and multi-section double track type. Single-section double-track: crawler robot [4], Packbot robot [5] and VSTR robot [6]; double-section double-track: China University of Mining and Technology proposed passive swing arm crawler robot [7] and Korea Institute of Science and Technology develops crawler passive adaptive robot [8], double-section dual track: North China Institute of Science and Technology designed flexible crawler mobile robot [9]; also the Chinese Academy of Sciences designed wheel composite robot [10], the front and rear quadrilateral suspension mechanism lunar rover [11].
This paper proposes a crawler-type passive adaptive robot. In order to improve the obstacle height of the robot and better adapt to the complex terrain environment, the structural design and obstacle-obstacle performance of the robot are analyzed and based on this optimization and simulation verification. This verifies the rationality of the robot’s obstacle-obstacle performance and structural parameter design.

2. Robot Structure Analysis

The tracked module structure of the crawler-type adaptive robot is mainly composed of a link mechanism, a crawler belt and a pulley. The linkage mechanism adopts a six-bar linkage design. According to the stability characteristics of the triangle, since a regular quadrilateral mechanism is a parallel mechanism, it is easy to deform and the direction and size of the deformation are easy to grasp, but it has an unstable performance for the obstacle-obscuring performance [12], and it is evolved into a five-bar linkage mechanism. It has the characteristics of large deformation and instability, and adopts two quadrilateral spliced link mechanisms, which evolves into a six-bar linkage mechanism. The mechanism is easy to deform, and the two quadrilaterals are mutually constrained, which overcomes the instability in the process of obstacle crossing. The six-bar linkage mechanism facilitates deformation and obstacles.

As shown in Fig. 1, $A_6A_3A_4$ is a fixed frame, $A_1A_2$, $A_2A_3$, $A_4A_5$, $A_1A_5$ and $A_1A_6$ links are a front link, a lower link, a rear link, an upper link, and an auxiliary link, respectively, and the links are connected by a rotating pair. Together, the other pulleys rotate around the wheel center. The deformation of the mechanism is that there is no original member, and the number of the original moving parts of the mechanism is less than the degree of freedom, so it is an underactuated mechanism. According to the law of minimum resistance, it can be concluded that the link mechanism moves in the direction with the least resistance. In the process of obstacle crossing, the impact force generated during the collision can be effectively reduced, and the longer the stability is improved.

![Figure 1. Structure diagram of the linkage mechanism](image-url)
3. Robotic Obstacle Mechanism

3.1 Robot Obstacle Analysis

The robot’s obstacle mechanism refers to the ability of the robot to pass certain road conditions [13]. Specifically, in a complex terrain environment (steps, climbs, trenches, etc.), the center of mass of the robot can cross the critical boundary line of the obstacle so that it does not rollover and recline, without obstacles being blocked, and has good passability. This paper mainly analyzes the topographical features of the steps and trenches, and uses the structural schematic diagram of the mechanism to analyze the obstacles in the process of obstacle crossing.

Tracked passive adaptive robots perform tasks in an unstructured environment. The non-structural environment is diverse, including rugged, rugged, stepped, and graded 3D terrain environments, and thus has a high level of robotic obstacle performance. The passive adaptive mechanism can adapt to the terrain. When encountering an obstacle, the deformation occurs under the action of the external force, so that the coordinate position of the center of mass of the robot changes, and the obstacle can be successfully climbed over the boundary line of the obstacle.

3.2 Robot Climbs the Stairs

When the crawler passive adaptive robot crosses the step, the angle between the track and the ground is called the elevation angle, and the elevation angle will gradually become larger. Under the premise that the flipping does not occur, the center of mass of the robot crosses the boundary line of the obstacle can achieve success obstacles. The whole process is divided into three phases:

a. The pulley of the front link of the track module comes into contact with the edge of the step. Under the action of the driving force, the robot moves slowly and uniformly, so that the front link and the lower link are deformed by force, and the robot moves up slowly, even the rod mechanism is deformed by force, As shown in Figure 2.

![Figure 2. Schematic diagram of the first stage of robot obstacle crossing](image)

b. When the gravity line of the robot just passes directly above the boundary line of the step, the boundary condition of the obstacle is reached. As shown in Figure 4, the elevation angle is known as $\theta$. The height of the step is $H$, the radius of the pulley is $R$, and the maximum height of the support of the tail wheel is $a$. The function that can be obtained is:

$$H(k, h, \theta) = R + a + (k - h \tan \theta) \sin \theta - \frac{R}{\cos \theta}$$  \hspace{1cm} (1)

It is determined in the formula that $R$, $a$, $k$ and $h$ are constants. $\theta$ to $H(k, h, \theta)$ make a first and second derivative:
\[
\frac{\partial H}{\partial \theta} = k\cos \theta - h\sin \theta \cdot \frac{(h + R) \sin \theta}{\cos^2 \theta}
\]
\[
\frac{\partial^2 H}{\partial \theta^2} = -k\sin \theta - h\cos \theta \cdot (h + R) \cdot \frac{\sin^2 \theta + \cos \theta}{\cos^3 \theta}
\]

Taking \(\theta \in (0, 2\pi)\), \(\frac{\partial^2 H}{\partial \theta^2} < 0\), \(H\) has a maximum value. When \(\theta_{\text{max}} = \arcsin \frac{h}{\sqrt{k^2 + h^2}} \in \left(0, \frac{\pi}{2}\right)\), \(H\) is \(H'_{\text{max}}\). So the conclusion that can be drawn is:

1. When the height of the step is less than \(H'_{\text{max}}\), the robot can smoothly cross the obstacle and not flip.
2. When the height of the step is greater than \(H'_{\text{max}}\), at the time, the robot will roll over or flip and cannot cross the obstacle.

**Figure 3.** Schematic diagram of the second stage of robot obstacle crossing

According to the above analysis, select the centroid of the robot \(G(k, h)\). The data of the middle 4 groups are: \(k=250\text{mm}, h=70\text{mm}; k=260\text{mm}, h=60\text{mm}; k=270\text{mm}, h=50\text{mm}; k=280\text{mm}, h=40\text{mm}\); \(R=28\text{mm}\) is known, \(a=40\text{mm}\) can be obtained from the equation 1 and the elevation angle of the robot. The relationship between \(\theta\) as shown in Fig. 4, is that when the center of mass of the robot is biased forward and downward, the obstacle height \(H\) of the robot is larger.

**Figure 4.** Curve of step height and elevation angle
c. Under the action of gravity and driving force, the robot's center of mass is continuously lowered, successfully crossing the steps.

3.3 Robot Climbs the Trench

The ability to cross the trench is also a major indicator of the obstacle performance of robots. The possibility of the track-type passive adaptive robot sloping trench depends mainly on the support point at both ends of the vehicle body, the distance between the projections of the center of gravity on the running surface, and the size of the slope angle. For the groove width is smaller than the track center distance, that is, \( a+b < B \), whether the pass in the slope can mainly depend on the relative position of the centroid and the support point of the slope.

When the robot passes through the sloping trench, it is necessary to ensure that the front end cannot fall into the trench and that the tail cannot fall into the trench. Since the position of the center of mass changes relative to the flat when driving on a slope, the schematic diagram of the width of the groove during the ascending process is shown in the figure. The width of the groove is:

\[
B = \min(a + h \tan \alpha, b - h \tan \alpha)
\]

Similarly, it can be concluded that the width of the gully when the slope is downhill is:

\[
B = \min(a - h \tan \alpha, b + h \tan \alpha)
\]

Figure 5. Schematic diagram of the robot climbing the trench

4. Structural Parameter Analysis and Optimization of Robot Track Module

4.1 Analysis of Structural Parameters of Track Module

The structural deformation of the track module adopts the quadrilateral structure design principle. The front quadrilateral \( A_1A_2A_3A_6 \) deforms under the action of external force and crosses the obstacle, while the rear quadrilateral \( A_1A_6A_4A_5 \) acts as a constraint on the front quadrilateral, preventing the deformation of the deformation mechanism from being too large, which is beneficial for the robot to be more stable in the event of obstacles.

As shown in fig. 6, the wheel center \( A_4 \) is established as the coordinate origin, the X axis coincides with the \( A_3A_4 \) frame, and the Y axis is perpendicular to \( A_3A_4 \). The angle between \( A_1A_2 \) and the X axis is \( \alpha \), the angle between \( A_2A_3 \) and the X axis is \( \beta \), and the angle between \( A_1A_3 \) and the X axis is \( \gamma \). The angle between \( A_4A_5 \) and the X-axis is \( \delta \), and the length of each rod is:

- \( \| A_1A_2 \| = L_1 \), \( \| A_2A_3 \| = L_2 \), \( \| A_3A_4 \| = L_3 \), \( \| A_4A_5 \| = L_4 \), \( \| A_5A_6 \| = L_5 \), \( \| A_1A_6 \| = L_6 \).

Parameter design requirements for rod length optimization:

a. The track module is within a certain range, and the total length of the rod is small, which reduces the overall quality of the robot.

b. During the deformation process, the link mechanism prevents the track and the pulley from derailing, and the total length of the track changes greatly.

c. The deformation mechanism of the track module can achieve better obstacle performance under a certain range of sizes.
Figure 6. Schematic diagram of the linkage mechanism

According to the design requirement a of the parameter, the rod length relationship between the links is established, and the distances of $A_1A_4$ and $A_1A_3$ are expressed as:

$$L_{A1A4} = \sqrt{(P_{A1} - P_{A4})^2} = L_1^2 + L_2^2 + L_3^2 + 2L_4L_5\cos(\alpha - \beta) + 2L_5L_6\cos\gamma$$
$$= L_1^2 + L_2^2 + 2L_4L_5\cos(\gamma - \delta)$$

$$L_{A1A3} = \sqrt{(P_{A3} - P_{A1})^2} = L_1^2 + L_2^2 + 2L_3L_4\cos(\beta - \alpha)$$

(3) 

(4)

4.2 Optimization Design of the Linkage Mechanism

According to the design requirements of the parameters b, the deformation of the track is small. The length of the track is a linear meshing section and a wheel arc engaging section of each pulley and the track, wherein each linear meshing section is a wheel center $A_1$, $A_2$, $A_3$, $A_4$ and $A_5$. The sum of the distances between adjacent ones is $\sum_{i=1}^{5} L_i$. The distance is a fixed value; the length of each arc engaging section is determined by the envelope angle between the pulley and the track and the radius of the pulley. In the closed chain link mechanism, the sum of the envelope angles of the track pulleys is 360°, and the length of the wheel arc engagement segments is constant only when the radius of each pulley is the same, which does not occur with the deformation of the link structure variety. In summary, the radius of each pulley is selected to be equal, and the performance of the obstacle is not affected.

According to the design requirements of the parameters c, the height of the wheel center $A_1$ is related to the obstacle-resisting performance, and the obstacle height determines the obstacle performance of the robot. Considering the quadrilateral mechanism, $L_1$ and $L_2$ and $\alpha$ . And the magnitudes of $\beta$, $L_3$ and $L_4$ and $\gamma$ and $\delta$ are related to the obstacle height. For the obstacle stability of the robot, the simulation analyzes the change of the centroid of each link to verify and verify.

The constraint conditions are the length range of each rod length, the design requirements for the centroid distribution of the connecting rod, the rod length relationship between the deformed connecting rods, and the height requirement of the undeformed crawler module. The optimal design of the connecting rod mechanism is adopted by Matlab.

In order to achieve the obstacle performance of the robot, the height variation of the wheel center $A_1$ is optimized and used as the objective function. By analyzing the link mechanism, due to the complicated structure and the large amount of parameters, the method adopted is to connect the link mechanism. Divided into two quadrilaterals $A_1A_2A_3A_6$ and $A_1A_5A_4A_6$ for analysis and calculation, according to the influence effect of two quadrilaterals, select the weighting factor representation. The design variables are:

$$X = [L_1 \quad L_2 \quad L_3 \quad L_4 \quad \alpha \quad \gamma]$$

(5)

The objective function is the difference between the maximum deformation and the undeformed height of the linkage:

$$\Delta h (X) = \max_\beta (h(\beta \setminus X)) - \min_\beta (h(\beta \setminus X))$$

(6)
According to the above analysis, the constraint conditions are self-constraints of independent variables, and the constraint equations without other independent variable functions can be transformed into unconstrained optimization problems by limiting the range of independent variables, and the objective function is optimized by coordinate rotation method.

According to the optimization problem, select the initial value of the parameter of the linkage:

\[
X_0 = \begin{bmatrix} 120 & 90 & 140 & 565 & 0 & \frac{\pi}{18} \end{bmatrix}
\]

The optimization problem is transformed into a mathematical function problem, and expressed in the M file by Matlab. The running solution and simplification can be concluded as follows:

\[
X = \begin{bmatrix} 117 & 95 & 135 & 560 & 0 & \frac{\pi}{15} \end{bmatrix}
\]

According to the geometric constraint relationship between the links, \(L_3=327\)mm, \(L_6=271\)mm can be obtained and the radius of the pulley is 28mm.

The optimization result is that the height of the wheel center \(A_1\) is compared with the change after optimization in the process of undeformed to maximum deformation. As shown in Figure 7, the optimized obstacle height has seen an increase. The total length of the link mechanism determines the weight of the robot. In order to reduce the weight, the total length of the connecting rod is reduced appropriately. The total length before optimization is \(L_0=1521\) mm, and the optimized total length \(L=1505\) mm.

![Figure 7](image)

**Figure 7.** Curve of the \(\beta\) angle and height \(h\) of the wheel center \(A_1\)

### 5. Simulation Analysis of the Linkage Mechanism

For the optimized linkage mechanism, the motion simulation is performed, and the centroid of each rod changes during the deformation process of the connecting rod. This section uses Adams software to analyze the kinematics of the deformation of the linkage mechanism. The centroid, speed and acceleration of each rod are analyzed. The obstacle-resistance performance is mainly related to the change of the centroid and the key rods are analyzed. As shown in Figure 8, it can be observed that the coordinate change of the centroid of the 1-front link is the largest, and the 5-upper link changes relatively slowly on the X and Y axes.
Figure 8. Changes in the centroid coordinates of the connecting rod

As shown in Figure 9, the speed of the center of mass of the connecting rod changes. Among them, the speed of the 1-front link changes a lot, while the 2-lower link and 4-rear link changes slowly. As shown in Figure 10, the acceleration of the centroid of the connecting rod is changed. The changes of the centroid acceleration of the 1-front link and the 5-upper link are relatively large, while 4-lower link is relatively slow.

Figure 9. Centroid speed change of the connecting rod

Figure 10. Change in centroid acceleration of the connecting rod

6. Conclusion
This paper analyzes the structural design of the linkage mechanism of the robot from the perspective of mechanism, with a degree of freedom of 1, which is an underactuated mechanism and uses carbon fiber material. According to the analysis of the obstacle mechanism of the robot, the mathematical model is established. When the position of the center of mass is lower and forward, the more favorable
the obstacle is the analysis and optimization of the rod length parameters of the linkage mechanism, and the optimized connecting rod Institutional simulation analysis to verify the rationality of the structural design and improve the obstacle performance of the robot. It can be concluded that the position of the center of mass of the robot and the maximum height of the wheel center a1 provide a theoretical basis for the optimal obstacle performance of the robot.

7. Acknowledgment
This work is supported by Hebei Province Applied Basic Research Program Key Basic Research Project (NO.17961820D).

8. References
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