Study on Characteristics of the Rope Grab Mechanism of a New Rope Climbing Robot

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Abstract. According to the design requirements of the horizontal rope rescue, a new rope climbing robot system based on the working mechanism of the cam type ascender is designed. This robot system is capable of free reciprocating movement on the preset horizontal ropeway and two-way self-locking at any position of the rope. This paper analyzes the design principle and structural characteristics of the two-way locking clamper, and designs the general structure of the robot system. Force analysis of grabbing process, development of the prototype and experiments are also done. The results show that the rope grab mechanism has advantages of small size, simple structure, reliable clamping and strong climbing ability. Moreover, this mechanism has good grabbing characteristics because of no relative slippage on the grabbing interface of the rope.

Introduction

The SRT (SINGLE ROPE TECHNIQUE) robot is a technology that uses automation devices to automatically lower and climb on a single rope. It can operate not only in a complex and small space, but also in a large span rescue. At present, the working mechanisms of rope climbing or cable climbing robots mainly includes transmission based on Euler-Eytelwein contact model¹, pneumatic or electric creeping²-⁴ and spiral climbing⁵. The effective transfer load of Euler-Eytelwein contact model depends on the friction coefficient of the grabbing interface and the contact angle, which has low transfer efficiency, and is not suitable for the rescue occasion where the ropeway has been preset. Creeping or spiral climbing is suitable for cableways with certain stiffness and is widely used in cable robots. However, its speed is relatively lower compared with continuous transmission mechanism, and the working reliability will be greatly reduced when operating on the rope with weak rigidity.

Based on the working mechanism of cam type ascender, this paper designs a system of rope grab mechanism with the ability of two-way swinging self-locking clamping, analyzes force characteristics of robot system, designs and develops the prototype and carries out experiments on it. The works ensure the load demand of the robot and good characteristics on the grabbing interface, and reduce the friction impairment to the rescue rope.

Model of Rope Grab Mechanism

Fig. 1 shows the typical structure of a mountaineering ascender, mainly comprising an ascender frame 2 and a clamping cam 3, and the rope 1 is located in the passage formed by the frame and the cam. When the ascender is pushed upward along the rope, the cam is driven downward by the friction of the rope to be in a released state, so the ascender and the rope can smoothly move against each other. On the contrary, when the ascender moves in the opposite direction, the cam is clamped due to the reverse friction of the rope, and the larger the load, the greater the clamping force. Therefore, compared with the transmission mode based on the Euler-Eytelwein contact model, such ascender has higher clamping reliability, and the relative movement between the rope and the
clamper is small, so the friction impairment to the rope is small as well\textsuperscript{[6]}. However, the mechanism is only suitable for one-way rising movement and cannot be applied to falling occasions.

Therefore, based on the working mechanism of the ascender, a novel clamper that can be applied to two-way movement along the rope is designed in this paper. As shown in Fig. 2, the clamper mainly comprises a clamper frame, left and right cam rollers, left and right clamping jaws.

Figure 1. Structure of ascender.
1-rope; 2-frame; 3-cam

Figure 2. Structure of a novel clamper.
1-rope; 2-frame; 3, 4-clamping jaws; 5, 6-cam roller

The cam roller 5, 6 are installed on the clamper frame through prismatic pairs, and can move linearly along two-way clamping directions shown in the figure, realizing the aim of clamping or releasing the rope. Each of the cam roller has a jaw that can swing about an O point (O\textsubscript{1} or O\textsubscript{2} in the figure). The jaw here plays the role of cam 3 in Fig. 1, while the jaw has a symmetrical structure so that it can clamp and lock the rope in both directions. The jaw's working mechanism is also similar to the cam in the ascender. When the rope and jaw have a relative moving tendency, the jaws are driven to rotate under the frictional force and then clamp the rope, and the larger the load, the greater the clamping force, achieving the purpose of locking the rope.

**Design of Horizontal Rope Climbing Rescuing Robot System**

Based on the above rope clamper, the movement of the robot along the rope can be achieved by several pairs of clammers periodically "clamping-traction-releasing" the rope. The detailed structure is shown in Fig. 3.
Figure 3. Detailed structure of the rescuing robot.
1-rope; 2-supporting rollers; 3-clampers; 4-motor; 5-side cam; 6-handler; 7-shaft 1; 8-adjust wheel; 9-shaft 2

The rope is supported by two supporting rollers 2 on both sides and forms a linear tensioning clamping passage below. Several clampers are mounted on the chain at equal intervals, and sprockets are mounted on shaft 1 and shaft 2 shown in the figure respectively. Shaft 2 is the driving shaft and is driven by a DC motor. The clamping and releasing of the rope are achieved by the linear motion of jaws driven by the roller at the end of each clamper, and the roller is driven by side cam 5. According to the state of the jaws, the rope passage can be divided into the Stage I-III section along the direction of rope as the figure shows. When the clamper's location is on the below side of the chain, or in Stage I or Stage III section, the clamper is in the released state; when the clamper is in Stage II section, it is clamped. If the motor drives shaft 2 rotating in the direction as the solid line indicates in the figure, clampers will move from the below side of the chain and pass through Stage I->Stage II->Stage III in turn. Clampers pass through the rope passage sequentially, completing the cycle of "into clamping - moving along the rope - exiting clamping" periodically, driving the robot to move in the direction as the solid line indicates in the figure, and vice versa (rotating direction and robot’s moving direction as the dotted line indicates).

**Force and Motion Analysis of Robot System**

This robot system is suitable for horizontal rope rescue. Since the rope passage itself has a certain sag, and the rope will elongate under a certain load, force characteristics of the system are complicated. For convenience of analysis, a coordinate shown in Fig. 4 is established, and main influencing parameters are marked out. X-O-Y is the global coordinate system, where X is the horizontal direction, and Y is vertical direction. Meanwhile, local coordinate system x-o-y is established, where x is the direction of hanging section AB of the rope----the direction of robot moving along the rope. The rope is divided into three approximate straight segments by the grab mechanism, forming a rear angle $\alpha$, a tilting angle $\beta$, and a front angle $\gamma$ relative to the X axis, respectively.
Assumptions are made as follows:
1) Frictional resistance of the supporting rollers on both sides is ignored. The rollers are mounted on the supporting shaft through bearings, so the friction force is relatively small and needn't to be considered in force analysis.
2) Loading approximately acts on the center of the robot body.
3) Weight of the rope is ignored.
4) Influence of wind load is not considered, and all loads are supposed to be static loads.

Therefore, the force analysis diagram can be established for the robot body and the rope segment AB respectively, as shown in Fig. 5.

1) Supporting condition equations:
   Establish force balance conditions for the support on A and B sides respectively. Suppose rope tension on forward side of the robot direction is T2, and rope tension on backward side of the robot direction is T1. The rope's support reaction for the A roller is R1 and for the B roller is R2, hence:

   Supporting condition equation of A roller: \[ R_1 = 2T_1 \sin \left( \frac{\alpha + \beta}{2} \right) \]  \hspace{1cm} (1)

   Supporting condition equation of B roller: \[ R_2 = 2T_2 \sin \left( \frac{\gamma - \beta}{2} \right) \]  \hspace{1cm} (2)

2) Force balance condition equation of the robot body:
   Suppose that the load G acts approximately on the center of the robot body and ignore the friction between supporting rollers and respective shafts. The clumper is securely clamped to the rope. F represents the driving force. Taking the robot body as the research object, the force balance equations in the x direction and the y direction are established:
\[ \sum F_x = 0: \quad R_1 \sin \left( \frac{\alpha + \beta}{2} \right) - R_2 \sin \left( \frac{\gamma - \beta}{2} \right) + F - G \sin \beta = 0 \quad (3) \]

\[ \sum F_y = 0: \quad R_1 \cos \left( \frac{\alpha + \beta}{2} \right) + R_2 \cos \left( \frac{\gamma - \beta}{2} \right) - G \cos \beta = 0 \quad (4) \]

3) According to Fig. 5 b), establish the rope tension balance condition

\[ T_1 + F - T_2 = 0 \quad (5) \]

According to the Eq. (1)-(4), first R1, R2 and T1 are eliminated, written as:

\[ 2 \left[ \sin^2 \left( \frac{\alpha + \beta}{2} \right) - \sin^2 \left( \frac{\gamma - \beta}{2} \right) \right] T_2 + \left[ 1 - 2 \sin^2 \left( \frac{\alpha + \beta}{2} \right) \right] F - G \sin \beta = 0 \]

\[ 2 \left[ \cos \left( \frac{\alpha + \beta}{2} \right) \sin \left( \frac{\alpha + \beta}{2} \right) + \cos \left( \frac{\gamma - \beta}{2} \right) \sin \left( \frac{\gamma - \beta}{2} \right) \right] T_2 - 2 \cos \left( \frac{\alpha + \beta}{2} \right) \sin \left( \frac{\alpha + \beta}{2} \right) F - G \sin \beta = 0 \]

Considering the rope tension balance condition Eq. (5), the relationship between the driving force F of the driving mechanism and the load G is as follows:

\[ F = \frac{C \sin \beta - A \cos \beta}{C B - D A} G \quad (6) \]

where:

\[ A = 2 \left[ \sin^2 \left( \frac{\alpha + \beta}{2} \right) - \sin^2 \left( \frac{\gamma - \beta}{2} \right) \right] ; \]

\[ B = 1 - 2 \sin^2 \left( \frac{\alpha + \beta}{2} \right) \]

\[ C = 2 \left[ \cos \left( \frac{\alpha + \beta}{2} \right) \sin \left( \frac{\alpha + \beta}{2} \right) + \cos \left( \frac{\gamma - \beta}{2} \right) \sin \left( \frac{\gamma - \beta}{2} \right) \right] ; \]

\[ D = -2 \cos \left( \frac{\alpha + \beta}{2} \right) \sin \left( \frac{\alpha + \beta}{2} \right) ; \]

**Analysis on Influences of Parameters**

Eq. (6) gives the relationship between the driving force and the robot load, the suspension rear angle \( \alpha \), tilting angle \( \beta \), and front angle \( \gamma \). During the moving process of the robot along the rope, rear angle \( \alpha \), tilting angle \( \beta \), and front angle \( \gamma \) vary dynamically. We can analyze the load characteristics of the robot at the extreme position, which provides a reference for the design. According to Eq. (6), the relationship diagram shown in Fig. 6 can be drawn:

![Figure 6. Influences of rope grabbing parameters.](a) (b)
1) The front angle $\gamma$ of the rope is the key parameter affecting the driving performance and load capacity of the rope grab mechanism. The larger the front angle, the greater the driving force required under the same load.

2) Increasing the rear angle $\alpha$ of the rope can improve the driving performance of the mechanism. However, considering the integrated requirements of the rescue site, the fixed anchor point of rope at distal end and the anchor point at proximal end should be at the same height as possible, then better comprehensive performance can be obtained.

3) Since we assume that the load acts approximately on the center of the drive mechanism, the tilting angle $\beta$ has little effect on the drive performance.

In practical applications, the angles vary with the position of the anchor point, the flexibility of the rope, the span $L$ between the supporting rollers of the drive mechanism, and the position of the robot system on the rope. The above analysis can explain the rope climbing process under extreme conditions for a reference in design.

**Design and Test of the Prototype**

A climbing prototype of the robot is developed for the above analysis. The span between the supporting rollers is taken as $L=330$mm. According to the project requirements and on-site prototype testing, in the case of extreme climbing condition, the rope's rear angle $\alpha$, tilting angle $\beta$, and front angle $\gamma$ are $10^\circ$, $40^\circ$ and $60^\circ$ respectively, and the load is 2500N. Considering a certain load factor of 1.5, based on Eq. (6), the required driving force can be calculated as 1935N. If the rope climbing speed is 200mm/s under extreme conditions, the power demand of the motor can be determined as $P = FV = 1935 \times 0.2 = 387$ W.

**Fig. 7. Prototype loading test.**

Fig. 7 shows the test of prototype, where the motor is the MOONS servo motor SSM24S with a rated power of 400W. The rope climbing robot prototype itself weighs 18kg. Under the load of about 250kg, the robot can move freely back and forth without slipping. The extreme climbing angle is about 65 degrees, meeting the designed goals.

**Summary and Conclusions**

This paper designs a rope grab mechanism system with the ability of two-way swinging self-locking clamping. This mechanism has advantages of small size, simple structure, reliable clamping and strong climbing ability. And because of no relative slippage on the grabbing interface of the rope, this mechanism has good application value. The development of the prototype shows that the mechanism has good load characteristics and can be self-locked by a two-way swing cam at any position, which has high safety performance.

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