Research and Optimization on PID Parameters for Driving System of a Novel Rope-Crossing Robot

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Abstract. A novel crossing-rope rescuing robot based on the working mechanism of the cam type ascender is designed in this paper. The mathematical model of the driving unit is established in order to get high driving performances, and self-tuning method of PI or PID parameters are discussed based on genetic algorithms. The case study shows the effectiveness of the model using GA optimization toolbox.

1. Introduction
Crossing rescue is an effective technical means of modern fire rescue, especially rescuing for islands, mountains and the likely occasions. Traditional crossing rescue is based on block and tackle or manual execution of firefighters, while the efficiency is very low and it will cause high risks to both victims and firefighters. The need of rescue technology based on rope crawling robot is increasingly urgent. Nowadays, the working mechanisms of rope climbing or cable climbing robots mainly includes transmission based on Euler-Eytelwein contact model[1], pneumatic or electric creeping[2-4] and spiral climbing[5]. 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.

This paper proposes an efficient rope crawling robot based on continuous-rope-grasping mechanism, which increases the load capability greatly comparing the Euler-Eytelwein contact model. Also, the mathematical model of the driving unit is established in order to get high driving performances, and self-tuning method of PI or PID parameters are discussed based on genetic algorithms.

2. Model of Rope Grab Mechanism
Comparing with the transmission mechanism based on the Euler-Eytelwein contact model, ascender based on cam engagement has higher clamping reliability, less relative movement between the rope and the clamper, so the friction impairment to the rope is smaller as well[6]. However, the mechanism is only suitable for one-way rising movement and cannot be applied to falling occasions. Fig.1 introduces a novel rope-grasping mechanism by using a pair of symmetrical cams. The pair of graspers consist of frame 2, frame 3, jaw 4, jaw 5, roller 6, and roller 7. Frame 2 and frame 3 can move relatively, forced by the passage forming by a floating cam 8 and a fixing cam 9, both cams have three profile segments, two introducing segments and one clamping segment. By this arrangement, different distances from the bottoms of the jaw 4 and jaw 5 can be obtained when a serious pairs of graspers are...
passing through the passage, specifically, with the minimal one equals \((0.6 - 0.8)d_0\), and the maximum one equals \((1.5 - 1.8)d_0\), and \(d_0\) is the rope diameter.

![Diagram showing rope clamping mechanism](image)

**Figure 1.** A novel rope grasping mechanism

Jaw 4 and 5 can oscillate about their own rotating points \(O_1\) and \(O_2\) respectively. Each jaw has a symmetrical cam-profile 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.

### 3. Design of Rescuing Robot Based on Symmetrical Cam Graspers

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. 2.

![Diagram showing robot structure](image)

**Figure 2.** Detailed structure of the rescuing robot. 1-rope; 2-supporting rollers; 3-clammers; 4-motor; 5-side down; 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 clammers 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, clammers will move from the below side of the chain and pass through Stage I->Stage II->Stage III in turn. Clammers 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).

4. Performance Analysis and PID Tuning of the Driving 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, so the load characteristics to the system are complicated. The driving unit of the robot can be modeled as a single input - single output system, the motion control system block diagram shown in Fig. 3. In order to get high performance of the driving system, the PID parameters need to be optimized.

![Figure 3. Motion control system block diagram](image)

According to the working principle of the servo motor, the principle diagram is shown in Fig. 4.

![Figure 4. Principle of the servo motor](image)

Thus, the mathematical model of the driving motor can be described as

\[
\begin{align*}
    u &= iR + L \frac{di}{dt} + e \\
    e &= K_e \frac{d\theta}{dt} \\
    T &= K_e i = f \frac{d^2\theta}{dt^2} + C \frac{d\theta}{dt} + M_c
\end{align*}
\]

Carrying out Laplace transform on the equations, we can get the transmission function as

\[
\frac{\theta(s)}{U(s)} = \frac{K_t}{Ls^2 + RJs^2 + K_eK_t} \quad (1)
\]
Where \( u \) is the input voltage of the motor, \( I \) is the loop current, \( R \) is the motor winding resistance, \( L \) is the winding inductance of the motor, \( e \) is the motor back EMF, \( K_e \) is the motor counter electromotive force constant, \( K_t \) is the torque constant, \( \theta \) is the motor rotation, \( T \) is the output torque, \( J \) is the moment of inertia, \( c \) is the viscous friction coefficient, and \( M_c \) is the load torque.

In this article the current loop and speed loop is controlled by the driver, using PI control; position loop gets access to the PID controller. Based on the reference [7], this paper creates a single input - single output control system block diagram, shown in Fig. 5. And \( K_m \) is the mechanical drive system parameters, \( K_{pi} \) is the scale factor of the current loop, \( K_{ii} \) is the integral factor of the current loop, \( K_{pv} \) is the scale factor of the velocity loop, \( K_{iv} \) is the integral factor of the velocity loop, \( K_{pp} \) is the scale factor of the position loop, \( K_{ip} \) is the integral factor of the position loop, and \( K_{dp} \) is the differential coefficient of the position loop.

\[
\begin{align*}
\text{position loop} & \quad u \to K_{pi} + K_{ii} + K_{pp} \quad \text{current loop} \\
\text{velocity loop} & \quad K_{pv} + K_{iv} \quad \text{output} = \frac{1}{K_m} \frac{J_s}{L_{Ds}} + R_s + K_a K_m
\end{align*}
\]

Figure 5. Control system block diagram

5. PID Parameter Tuning based on Genetic Algorithm

Genetic Algorithm (GA) simulating biological heredity and evolution in the natural environment is an adaptive global optimization probabilistic search algorithm. In the genetic algorithm, the fitness function directly affects the performance of the genetic algorithm, which is an important basis for the copy operation. The fitness function is generally defined as the reciprocal of the objective function, as the following equation

\[
F(x) = \frac{1}{J(x)} = \frac{1}{\int_{0}^{\infty} \omega_1 e(t) dt + \omega_2 t_s + \omega_3 \sigma + \omega_4 t_p}
\]  

(2)

Where \( \omega_1 \) (\( i = 1,2,3,4,5 \)) is a weighted value, \( e(t) \) is the error function of the system, \( u(t) \) is the controller’s output, \( t_s \) is the adjustment time, \( \sigma \) is the s overshoot, \( t_p \) is the peak time.

The main requirement in the control system is reliability and stability. In this paper, step signal is the input, and the output curve reflects performance of the system. For the step response curve, adjustment time \( t_s \) reflects the rapidity and accuracy, overshoot \( \sigma \) reflects stable performance and system control precision, and peak time \( t_p \) reflects speed of the system, totally showing the rapidity, stability and accuracy [8]. Error integral indicators can show the dynamic characteristics of the system processes. Common error integral indicators are IE, ISE, IAE, IATE and ISTE, and this paper selects IAE as the performance indicators. Meanwhile, adding integral squared term of the controller output to the objective function is able to prevent excessive control. Based on genetic algorithm, this article will perform tuning on current loop parameters \( K_{pi} \) and \( K_{ii} \), velocity loop parameters \( K_{pv} \) and \( K_{iv} \), and the position loop parameters \( K_{pp}, K_{ip} \) and \( K_{dp} \), so that the motor is running the best.

According to the function block diagram shown as fig.5, we can optimize the parameters from the inner current loop to out position loop successively. The transfer functions can be defined at each loop, then we can define the fitness function according to equation (2) respectively. The solving procedure can be given as in the following Fig.6.
Define fitness function (2) as “minf” with Matlab function, call it in Matlab GA toolbox, set the population size \( n \) to be 100; the range of generations is 200; crossover rate \( P_c \) is 0.9; Mutation Rate \( P_m = 0.10 - \frac{[1:1:n] * (0.01)}{n} \). The weighted values of the objective function are \( \omega_1 = 0.999, \omega_2 = 0.001, \omega_3 = 6, \omega_4 = 2, \omega_5 = 4 \). The optimum results are shown as in Table 1.

### Table 1. PID parameters of the driving unit

| Parameters | \( K_{pi} \) | \( K_{ii} \) | \( K_{pv} \) | \( K_{iv} \) | \( K_{pp} \) | \( K_{ip} \) | \( K_{dp} \) |
|------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Value      | 19.95        | 0.82         | 5.15         | 9.78         | 19.26        | 0.14         | 0.15         |

A step signal is applied to the model in Simulink in order to verify the performances before and after optimization. It shows the control system's stability accuracy, dynamic and static performance from many aspects have been improved after optimization.
6. 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. An optimization model of PID parameters of the driving unit of the robot is investigated in order to increase the load capability and working reliability. A prototype is designed with the maximum load as 225kg, verified the effectiveness of the model and methods the paper discussed.

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8. References
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