The kinematic and dynamic characteristics and system optimization design of optical cable based on backtracking method

Yongchi Lin¹, Jie Li¹, Shouqiang Zheng¹, Zhenzhu Shen¹, Weicheng Huang¹, Jinling Song², Fengshun Liang³ and Lizhi Gu¹,*

¹ Key Laboratory of Virtual Manufahturer Technology of Fujian University, Quanzhou University of Information Engineering, No. 249, Bodong Road, Fengze District, Quanzhou, Fujian, China, 362000
² Quanzhou Normal University, No.398 Donghai Boulevard, Fengze District, Quanzhou, Fujian, China, 362000
³ Fujian (quanzhou) Harbin Institute of Technology, Building 9, Quanzhou Software Park, Fengze District, Fujian, China, 362000

*Corresponding Author, gulizhi888@163.com

Abstract. Optical cable in modern communications is an important facility, and the laying of the optical cable is the key link in the installation. On the basis of analyzing the technological process and ensuring the requirements of optical cable laying, the kinematic parameters the tractor was first optimized and determined by the simplex method. Analyzing the motion state and stress state of optical cable laying. Exponential function was selected as the movement mode of the cable to start and stop the cable. The kinematic characteristics of optical cable were programmed with the simplex method, and the optimal acceleration, uniform speed and deceleration distance were obtained corresponding to the three stages. Then the ideal parameters of cable cable's velocity and acceleration were determined. According to this, the angular acceleration as well as other kinematic and dynamic characteristics of the roller slip roller was obtained ensuring these parameters being in coalescence with those of the tractor. The application study has shown that the system works well and meets the design expectation.

1. Introduction
Optic cable is an important facility in modern communications with proper laying out of the cable. At present, there are three basic process methods. First, depending on manual operation, the labor intensity of the workers is large, the production efficiency is low. Second, partial mechanization, reduced labor intensity, work efficiency is still not high. The third is automation and intelligence, representing the direction of the development of optical cable direction. Its basic technology includes the cable in the roller wreath slide pull out technology, the directional export technology and the pulley drive and the cable traction coupling technology. However, there are still problems such as low efficiency and damage to the cable sheath in out-laying. Rozorinov H et al. [1] studied the bending radius of optical cable wiroller and proposed to ensure the reasonable radius under the communication function. Choi J K et al. [2-4] used a remote control car to lay underwater optical cables, and successfully installed DONET2 on the bottom of the sea to predict earthquakes and tsunamis. Butler B et al. [5] developed a complete set of technical equipment for cable laying under
the ice sheet for this environment, including vehicle design, energy storage, navigation, control, cable laying, logistics support and communication technologies. Chen Q et al. [6] explored the constant tension controller with FUZZY P + ID hybrid control strategy, which effectively realized the constant cable tension between the cable laying vessel and the radiator. Canas V et al. [7] used PLC to realize automatic laying of railway cables to ensure the stability of tension. Muneez M et al. [8] compared and studied the advantages and disadvantages of laying cables on the seabed using the ploughing method and the water-flushing method, and proposed the adoption of new trench laying technology to avoid the damage to the seabed ecology. Wang Z F et al. [9] studied and proposed an anti-seismic design algorithm for laying optical cables across earthquake-prone zones and other complex and sensitive zones. Different protection measures were applied to different sections in different situations. Meng C H et al. [10-12] designed a mechanical cable out-laying device, and partly realized remote control.

The current study aims at optimized automatic out-laying system of optical cable, with system optimization design based on backtracking method.

2. Processing analysis and basic requirements of automatic out-laying of the cable

The cable is wound on the roller slip roller before laying. Into the construction phase, the cable must be in a certain way from the slip roller on the export, straight. In this process, the direct tension of the cable should not be greater than 80% of the maximum allowable tension. At the same time, the cable should maintain the mechanical performance, environmental performance, chemical corrosion resistance. The tinted ink color is supposed to prevent from damage by stretching or winding back of the cable.

3. System composition and overall functional design

The optical cable automatic laying system is mainly composed of roller slip roller, servo motor, permanent magnet couple, slot track and tractor, as shown in figure 1. The servo motor drives the drum to rotate through the permanent magnet couple, and at the same time makes the tractor (hereinafter referred to as the trolley) move synchronously on the track with the linear speed of the release point of the roller slip-roller, so as to flatten and straighten the optical cable wrapped in the slide roller along the track slot until the length L is reached. At this time the drum and the car stop moving. Both the servo motor and the tractor motor can control the output speed to meet the dynamic and kinematic requirements of the outgoing line.

![Figure 1. Composition and working principle of cable laying out system](image)

4. Distribution and programming of stretch velocity using simplex method

In order to realize the overall functional requirements of the system, the inverse method is adopted to optimize the kinematic parameters of the traction cable first, and then the optimized results are taken as known conditions to make the stepper motor of the driving drum match, and to analyze and determine the kinematic and dynamic parameters of the roller slip roller.
Suppose the tractor pulls out the cable in a directional way through the guide rail. Taking the time to pull out the cable and make it flat as the objective function, and the distance corresponding to acceleration, uniform speed and deceleration as the decision variable \( X = \{x_1, x_2, x_3\} \), simplex method is adopted to plan the laying out line, which is visible

\[
\begin{align*}
\text{min } f(X) \\
\text{s.t. } g_i(X) = 0 \\
X \geq 0 \\
X = \{x_1, x_2, x_3\}
\end{align*}
\] (1)

where \( X = \{x_1, x_2, x_3\} \) are the distances of accelerating stage, uniform stage, and decelerating stage, respectively.

In order to improve the line setting efficiency, it is considered to simplify the calculation and make it easy to control. The distances in the accelerating stage and the decelerating stage are taken with the same value, i.e., \( x_1 = x_3 \). Meanwhile, the approximate average speed \( v_{\text{ave}} = \sqrt{2} v_0 / 2 \) is taken into account in the variable speed stages. Now the objective function is expressed in terms of

\[
f(X) = 2\sqrt{2} \frac{x_1}{x_0} + \frac{x_2}{x_0}
\] (2)

Constraint conditions are

\[
\begin{align*}
2x_1 + x_2 - L &= 0 \\
x_1 - 10 &\leq 0 \\
x_1, x_2, x_3 &\geq 0
\end{align*}
\] (3)

By using simplex method, the optimal solution to this linear programming problem is:

\[
x_1 = 10 \\
x_2 = L - 20 \\
x_3 = 10
\]

Suppose that \( L = 200 \text{m} \), then \( X = \{10, 180, 10\} \), and time spent \( f(X) = 20.828 \text{s} \).

The \( e \) index function is selected as the motion mode of cable starting and ending to reduce the impact force of starting and stopping. The corresponding acceleration stage, uniform stage and deceleration stage are taken as follows:

\[
\begin{align*}
v_1 &= v_0 \left(1 - e^{-\frac{t}{\tau}} \right) \\
v_2 &= v_0 \\
v_3 &= v_0 \left(e^{-\frac{a+b-t}{\tau}} \right)
\end{align*}
\] (4)

The velocity \( v_0 \) is desirable at 10m/s. That corresponds to the acceleration of the first stage

\[
\alpha_1 = \frac{dv_1}{dt} = v_0 \frac{1}{\tau} e^{-\frac{t}{\tau}}
\] (5)

The acceleration requirement can be satisfied by selecting and determining the appropriate time constant.

Cable speed and acceleration planning are as follows:

Take the velocity curve as 3 stages, see figure 2. The velocity curves of the three stages are respectively \( e \) exponential acceleration, uniform velocity and \( e \) exponential deceleration, and the corresponding time periods are respectively \( a, b \) and \( c \).
The velocities of the three stages are given by equation (4). The acceleration can be obtained by taking the derivative of the corresponding velocity with respect to time. The first acceleration is shown in equation (5). The other two accelerations are not described.

\[ p_1 = v_0 \left[ t + \frac{v_0 t}{a+b} \right] \]
\[ p_2 = v_0 t \]
\[ p_3 = -v_0 e^{-\frac{t}{\tau}} \]

5. Dynamic and kinematic parameters analysis and determination of roller slide roller

As mentioned above, the servo motor drives the drum to rotate through the permanent magnet couple, and simultaneously causes the tractor (hereinafter referred to as the trolley) to move synchronously on the track with the linear speed of the release point of the roller slip-roller, so as to flatten and straighten the cable wrapped in the slide roller along the track slot until the length L is reached. According to the above optimized motion parameters, the dynamic and kinematic parameters of the roller slip roller are obtained.

5.1. Fundamental assumptions

The cable is supposed as the cylindrical ribbon cable, diameter d, glass core with external protection materials. Let the uniform integrated mass per unit-length, \( m_l \), of the continuous cable be 18 kg/1000 m. It is layered and tightly wound on the cable slip roller. When the cable is unrolled and rolled back respectively, the mass of the drum obeys the following rules

\[ M_1 = M_{01} - \int_0^t m_1 v dt \] when the cable is stretched \( (7) \)

\[ M_2 = M_{02} - \int_0^t m_1 v dt \] when the cable is rolled. \( (8) \)

where \( M_1 \) and \( M_2 \) are the instantaneous mass of the roller when the cable is unrolled and rolled back respectively. \( M_{01} \) is the mass of the drum at full load, \( M_{02} \) is the mass of the drum at no load, and \( v \) is the instantaneous speed of the cable.

Operating diameter of slide roller (minimum operating diameter of drum) \( d_1 \); the maximum working diameter of the roller is \( d_2 \), and the working width is \( w \) (integer multiple of the cable diameter \( w=n \times d \)).
5.2. Analysis of moment of inertia

According to figure 3, the definition of the moment of inertia of a cylinder rotating around a fixed axis:

\[ J = J_{\text{slide}} + J_{\text{cylinder}} + J_{\text{stress}} + J_{\text{cable}} = 13.74 (\text{kg} \cdot \text{m}^2) \] (9)

5.3. Arrangement of the cable in the slide roller

The cable is so arranged in the winding arrangement of the roller slip roller that it may be stretched or wound back with ease, see figure 4. In this case, The total capacity of the slide roller is

\[ L_i = \sum_{k=0}^{n_{i+1}-1} (d_i \cdot t) \] (10)

where \( n_{i+1} \) is the number of optical cable turns on the slide roller layer; \( d_i \) is the equivalent diameter of the roller on layer \( i \).

6. Conclusions

For optimized optical cable automatic out-laying system, the current study began with the desired results, then the motion parameters and dynamic parameters of the roller slide roller were retrospectively calculated, and the structural parameters were determined and the working parameters of the tractor were matched. The method of simplex has been successfully used to plan the kinematic characteristics of cable laying out, and the optimal distances of acceleration section, uniform section and deceleration section were obtained.

The \( e \) index function was selected as the motion mode of cable starting and ending, and the middle section adopts uniform linear motion mode to ensure that the theoretical impact force of cable starting and stopping is zero. The ideal optical cable displacement, velocity and acceleration parameters have been obtained. The acceleration of the cable was adopted to back out of the slip roller angular acceleration. Parameters of the roller were obtained by using the relation of rotary torque, moment of inertia and angular acceleration. It has shown that the system works well and meets the design expectation.
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