Application of Improved S-Curve Flexible Acceleration and Deceleration Algorithm in Smart Live Working Robot

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Abstract. Smart live working robot incorporates the merits of security and reliability, which can greatly improve automation rate of living working, suitable for power distribution network live working applications. Due to flexible strike and shake in automatic stripping wire module of smart live working robot start and end period, an improved S-curve flexible acceleration and deceleration control method is proposed. Based on analyzing disadvantage of conventional linear and exponential acceleration and deceleration algorithm, formula math model of improved cubic polynomial S-curve acceleration and deceleration algorithm is derived. Five-paragraph format motion planning is adopted the proposed S-curve control method, which can realize appointed acceleration and deceleration time moving. Meanwhile, the acceleration is continuous during moving period, and according to different working condition, different S-curve type can be chose. The simulation and practical operating results showed that proposed control strategy can effectively reduce flexible strike, thus improving stationarity and accuracy of the control system.

1. Introduction

With the continuous social and economic development of China, people, enterprises and individuals are heavily dependent on electricity for daily needs. As a result, the contradiction between the need for power outages when grid transformation is undertaken and people's demand for uninterrupted power supply is becoming more and more prominent [1-2]. In order to meet the demand for uninterrupted power supply, strengthen daily maintenance, and build a safe defense system for the power system, power grid companies must follow the principle of "Live Working First" during the work on the distribution lines, that is, the work shall be performed in the form of live working as far as possible, to improve the stability and reliability of power supply. Live working usually includes line stripping, live working, line clamp fittings installation. The traditional manual live working requires more than one person to operate on the transmission lines at the same time, which is difficult, time-consuming, and inefficient. Moreover, due to frequent lifting and nervousness, personal injury and death often occur. Compared with manual live working, the intelligent live working robot is composed of a multi-degree-of-freedom robot arm, modular live working tools, insulation protection system, etc. With the robot, the requirements of complex practical use environments can be met, the safety, stability, and convenience of the operation process can be ensured, and the labor intensity and safety risk of the operators can be greatly reduced. In doing so, the personal safety of the operators can be effectively...
ensured, further promoting the automation of live working. It not only has important social values but also has a broad application prospect in the live working in the power distribution grid [3].

The automatic insulation line stripping module of the intelligent live working robot operates in a circular arc cutting motion along the tangential direction of the wire. The sudden change in velocity at the start and end of deceleration can easily produce shocks, which can seriously affect the stability and accuracy of the robot components stripping. Besides, the components themselves can also cause wear and tear, affecting the service life. In order to reduce the shocks, improve operation accuracy, and achieve high-velocity machining, the control of acceleration and deceleration is usually used in the motion system. The traditional trapezoidal and exponential acceleration/deceleration algorithms are suitable for point control, but due to the discontinuity of acceleration, they can lead to large shocks and vibrations, which affect the quality of machining and make it difficult to achieve high precision control [4]. S-curve acceleration and deceleration algorithms can greatly improve the shortcomings of the traditional acceleration and deceleration algorithms. In the traditional acceleration and deceleration algorithms, the whole moving process is divided into seven stages, that is, accelerated acceleration, uniform acceleration, decelerated acceleration, constant velocity, accelerated deceleration, uniform deceleration, and decelerated deceleration. The velocity is smoothed out to reduce flexible shocks. However, since there are many classification cases and a great number of parameters involved, the algorithm is hard to implement [5-6]. The literature [7-8] improved the smoothness of system motion by using a trigonometric function method, but trigonometric functions were hard to calculate and would increase the operational burden of the system. Some scholars introduced intelligent algorithms into acceleration and deceleration control. The literature [9] proposed an S-curve acceleration and deceleration method based on genetic algorithms to achieve better and more accurate operations. However, due to poor stability and high complexity, the intelligent algorithm is difficult to be applied in embedded motion control systems.

In this paper, the automatic insulated conductor stripping module of the intelligent live working robot is taken as the control object. To address the problems such as flexible shocks and vibration that exist when the operation start and end, the traditional trapezoidal algorithm is analyzed and an improved S-curve flexible acceleration and deceleration algorithm is proposed. Based on the cubic polynomial acceleration and deceleration mathematical model, the proposed acceleration and deceleration algorithm uses five-stage motion planning. The algorithm not only is simple to implement but also can ensure the continuity of acceleration, resulting in a smooth velocity operation and smaller flexible shocks for the system. Simulation and actual operation results verify the effectiveness of the algorithm.

2. Traditional Acceleration and Deceleration Control Algorithm

2.1. Trapezoidal Acceleration and Deceleration Control Algorithm

Fig. 1 shows the schematic diagrams of the trapezoidal acceleration and deceleration control algorithm, including velocity curve, acceleration curve, and accelerated acceleration curve. It can be seen from the figure, trapezoidal acceleration/deceleration control is divided into three segments, that is, constant acceleration segment, constant velocity segment, and constant deceleration segment. At the start or end time, the velocity increases or decreases in a straight line with a fixed slope $A_g$. 

\[ v(t) = \begin{cases} 
A_g t & \text{if } 0 \leq t < t_1 \\
A_g t_1 & \text{if } t_1 \leq t < t_2 \\
v_0 & \text{if } t_2 \leq t < t_3 \\
A_g t_3 & \text{if } t_3 \leq t < t_4 \\
v_0 - A_g (t - t_4) & \text{if } t_4 \leq t < t_5 \\
v_0 - A_g (t - t_5) & \text{if } t_5 \leq t < t_6 \\
v_0 - A_g (t - t_6) & \text{if } t_6 \leq t < t_7 \\
v_0 - A_g (t - t_7) & \text{if } t_7 \leq t \leq T_7 
\end{cases} \]
2.2. Exponential Acceleration and Deceleration Control Algorithm

The exponential acceleration and deceleration control algorithm is shown in Fig. 2. The exponential acceleration and deceleration control algorithm consists of three segments, that is, the exponential acceleration segment, the constant velocity segment, and the exponential deceleration segment. At the start or end time, the velocity increases or decreases according to the exponential change law.

The velocity of the acceleration segment is expressed as follows:

\[ v(t) = v_g \left(1 - e^{-t/\lambda}\right), \quad 0 \leq t < t_1 \]  \hspace{1cm} (1)

The velocity of the constant velocity segment is expressed as follows:

\[ v(t) = v_g, \quad t_1 \leq t < t_2 \]  \hspace{1cm} (2)

The velocity of the deceleration segment is expressed as follows:

\[ v(t) = v_g e^{-t/\lambda}, \quad t_2 \leq t \leq t_3 \]  \hspace{1cm} (3)

where \( v_g \) is the target velocity and \( \lambda \) is the time constant.

Although the traditional trapezoidal and exponential acceleration and deceleration algorithms are simple to implement, there are certain shortcomings. From Fig.1 and Fig.2, it can be seen that the trapezoidal acceleration and deceleration algorithm has four pulse shocks in the whole moving process, and the exponential acceleration and deceleration algorithm has two pulse shocks in the whole moving process. The discontinuity of acceleration will cause flexible shocks in the machining process, further affecting system motion smoothness and machining accuracy as well as the service life of the system. Further, affecting system motion smoothness and machining accuracy as well as service life of the system equipment.
3. Improved S-Curve Flexible Acceleration and Deceleration Control Algorithm

To overcome the shortcomings of the traditional trapezoidal and exponential acceleration and deceleration algorithms, improve the smoothness of operation, and enhance the machining accuracy, the S-curve acceleration and deceleration algorithm is usually used. Because the velocity shows an S-shaped curve in the acceleration and deceleration process, the curve is called “S-curve”. Although the 7-segment S-curve, which is commonly used at present, has good running smoothness and high accuracy, it has many running segments and large calculation volume and the algorithm is hard to implement, which greatly increases the operational burden of the system.

To reduce the impact of flexible shocks on the machining operation, achieve better control performance, and make the control algorithm simple and easy to implement, this paper proposes an improved S-curve flexible acceleration and deceleration control method.

Acceleration and deceleration control refers to the planning of velocity at different stages of operation. During the whole velocity planning process, the relationship between accelerated acceleration, acceleration, velocity, displacement, and time can be expressed as follows:

\[
\begin{align*}
    a(t) &= a_{i0} + \int_{0}^{t} j(t) \, dt \\
    v(t) &= v_{i0} + \int_{0}^{t} a(t) \, dt \\
    s(t) &= s_{i0} + \int_{0}^{t} v(t) \, dt
\end{align*}
\]  

(4)

where \( j \) is the accelerated acceleration, \( a_{i0} \) is the initial value of acceleration, \( a \) is the acceleration, \( v_{i0} \) is the initial value of velocity, \( v \) is the velocity, \( s_{i0} \) is the initial value of displacement, and \( s \) is the displacement. From Equation (4), it can be seen that the acceleration is an integral of accelerated acceleration over time, the velocity is an integral of acceleration over time, and the displacement is an integral of velocity over time. Different mathematical expressions of accelerated acceleration, acceleration, and velocity will present different methods of velocity planning.

![Fig. 2 Exponential Acceleration and Deceleration Diagram](image-url)
In order to reduce flexibility shocks and achieve smooth machining operation, the acceleration must be continuous during the acceleration and deceleration planning. The velocity curve of the proposed improved S-curve acceleration and deceleration algorithm is constructed by a cubic polynomial function, which can be expressed as follows:

\[ v(\alpha) = \left(a_0 + 2a_2\alpha + 3a_3\alpha^2 + 4a_4\alpha^3\right) / t_n \]  

where \( \alpha = t/t_n \), \( t_n \) is the time required for acceleration or deceleration, \( 0 \leq t \leq t_n \).

The expressions for the acceleration curve \( a \) and the accelerated acceleration curve \( j \) can be obtained by deriving Equation (5) once and twice, respectively, as follows:

\[
\begin{align*}
    j(\alpha) &= (6a_3 + 24a_4\alpha) / t_n^3 \\
    a(\alpha) &= (2a_2 + 6a_4\alpha + 12a_5\alpha^2) / t_n^2
\end{align*}
\]  

Through the integration of Equation (5), the displacement s-curve function can be expressed as follows:

\[ s(\alpha) = a_0\alpha + a_2\alpha^2 + a_3\alpha^3 + a_4\alpha^4 \]  

Because the absolute displacement is obtained by translational motion, the following boundary conditions shall be met. The starting displacement is 0, the starting and ending velocities are the same as the given velocity, and starting and ending accelerations are 0. The boundary conditions mentioned above can be expressed as follows:

\[
\begin{align*}
    a(0) &= a(1) = 0 \\
    v(0) &= v_s \\
    v(1) &= v_e \\
    s(0) &= 0
\end{align*}
\]  

where \( v_s \) is the starting velocity and \( v_e \) is the ending velocity.

Substituting the above boundary conditions of Equation (8) into Equations (5) to (7), the accelerated acceleration, acceleration, velocity, and displacement curve functions based on the cubic polynomial acceleration and deceleration algorithm can be obtained as follows:

\[
\begin{align*}
    j(\alpha) &= 6(v_e - v_s)(1 - 2\alpha) / t_n^2 \\
    a(\alpha) &= 6(v_e - v_s)(\alpha - \alpha^2) / t_n \\
    v(\alpha) &= v_s + 3(v_e - v_s)\alpha^2 + 2(v_e - v_s)\alpha^3 \\
    s(\alpha) &= t_n v_s\alpha + (v_s - v_e)\alpha^2 + 0.5(v_e - v_s)t_n\alpha^4
\end{align*}
\]  

From Equation (9), it can be seen that in the acceleration or deceleration process, the graph of the acceleration \( a \) is a quadratic parabolic curve, and the graph of the velocity \( v \) is a cubic polynomial curve. Based on Equation (9), the velocity planning of the whole acceleration and deceleration process can be completed to achieve smooth operation.

In order to adapt to different working conditions, the velocity planning cubic polynomial based on Equation (9) is multiplied by quadratic polynomials with different coefficients respectively to provide different S-curve transition forms. When \( 0 \leq \alpha \leq 0.5 \), the expressions are as follows:

\[
\begin{align*}
    v_{s\alpha0}(\alpha) &= v(\alpha) , \quad \text{Type0} \\
    v_{s\alpha1}(\alpha) &= v(\alpha)(2\alpha^2 - \alpha + 1) , \quad \text{Type1} \\
    v_{s\alpha2}(\alpha) &= v(\alpha)(4\alpha^2 - 2\alpha + 1) , \quad \text{Type2} \\
    v_{s\alpha3}(\alpha) &= v(\alpha)(8\alpha^2 - 4\alpha + 1) , \quad \text{Type3}
\end{align*}
\]  

As shown in Equation (10), four different types of S-curves in the acceleration or deceleration stage are given. Based on the middle point-velocity symmetrical relationship in the acceleration (deceleration) planning, when \( 0.5 \leq \alpha \leq 1 \), i.e., the acceleration or deceleration stage, the acceleration (deceleration) planning of the entire process can be completed by replicating the first half of the velocity curve.
4. Simulation Analysis

A simulation model of the improved S-curve acceleration and deceleration algorithm is established in MATLAB/Simulink to verify the effectiveness of the proposed control algorithm. In the simulation process, the starting velocity of the motor is 0, the target velocity is 3000rpm, the acceleration time is 300ms, the moving time with constant velocity is 400ms, and the deceleration time is 300ms.

Fig. 3 shows the simulation curve waveform of the improved S-curve flexible acceleration and deceleration algorithm based on cubic polynomials. From the figure, it can be seen that the velocity curve is planned into five stages, that is, accelerated acceleration, decelerated acceleration, constant velocity, accelerated deceleration, and decelerated deceleration. When \( t = 0 \)s, the motor starts acceleration at 0rpm, and the acceleration reaches the maximum value when \( t = 150 \)ms. When \( t > 150 \)ms, the acceleration decreases, and the motor enters the decelerated acceleration stage. When \( t = 300 \)ms, the motor reaches the target velocity of 3000rpm and starts moving at a constant velocity. At this time, the acceleration is 0. When \( t = 700 \)ms, the motor enters the accelerated deceleration stage. When \( t = 850 \)ms, the motor enters the decelerated deceleration stage. At this time, the acceleration decreases negatively and the motor velocity decreases further. When \( t = 1000 \)ms, the motor velocity decreases to 0. It can be clearly seen that in the whole velocity planning, the acceleration is always continuous and the velocity curve is S-shaped during acceleration and deceleration, which can effectively reduce the flexible shocks of operation and improve the stability of operation.

Fig. 3 Simulation Curve Waveform of Improved S-curve Flexible Acceleration and Deceleration Algorithm

Fig. 4 shows the simulation waveforms of S-curves with different transition forms. From the figure, it can be seen that the acceleration curvature of four different types of S-curves is different. According to the different requirements of different working conditions, an optimal S-curve can be selected to achieve the best control performance.
Fig. 4 Simulation Waveforms of S-curves with Different Transition Forms

5. Experimental Verification
To further verify the control performance of the improved S-curve flexible acceleration and deceleration algorithm based on cubic polynomials proposed in this paper, an experimental study was conducted. As shown in Fig. 5, the live working robot system platform is mainly composed of a UR10 robotic arm, a line stripping module, a live working module, a coating module, an insulating rod, and a computer. The robotic arm is controlled by computer programs to pick up the line stripping, live working, and coating modules to complete a series of live working operations.

Fig. 5 Live working Robot System Platform

Fig. 6 Schematic Diagram of Line Stripping Module

Fig. 6 shows the schematic diagram of the line stripping module involved in this paper. The module mainly consists of main tine, guide fork, open-close tine, stripping tool, closing motor, stripping motor, control board, etc. The robotic arm lifts the line stripping module to the below of the cable, and along the guiding fork to the initial position of the stripping. Then the closing motor starts to close the open-close tine and lock the cable to the stripping slot. The stripping motor starts the tool for stripping operation. The main control chip of the control board is STM32F407, and the motor control adopts velocity-current double closed-loop PI control.
Fig. 7 Flow Chart of Line proposed in this paper, which improves the smoothness and accuracy

Stripping Operation

The flow chart of the line stripping operation is shown in Fig. 7. The S-shaped curve is discretized by timer interrupt of the STM32F407 for velocity planning. Through the presetting of the given velocity (3000rpm), acceleration time (0.3s), and deceleration time (0.3s), the velocity curve planning is achieved. Fig. 8 shows the experimental velocity curve of the stripping motor, which is plotted using MATLAB by saving the velocity data in arrays and uploading it to the computer through the serial ports. From the figure, it can be seen that the motor motion is planned in five stages. When \( t=0 \), the starting velocity of the motor is 0. After the accelerated acceleration and decelerated acceleration stages, when \( t=0.3 \text{s} \), the motor reaches a given velocity and starts to move at a constant velocity. When \( t=0.7 \text{s} \), after the accelerated deceleration and decelerated deceleration stages, the motor decreases from 3000rpm to 0 in terms of velocity. It can be seen that the motor velocity changes in an S-shaped curve with the preset given velocity, acceleration, and deceleration time.

Fig. 9 shows the stripping operation and the final effect. It can be seen from the figure that the stripping position of the cable is intact, the cable core is not damaged, and there is no obvious residue of the cable skin. The results verify the effectiveness of the improved S-shaped flexible acceleration and deceleration algorithm of operation.
6. Conclusion

In this paper, an improved S-curve flexible acceleration and deceleration control method was proposed to address the problems of flexible shocks and vibration when starting and ending the automatic line stripping module of the intelligent live working robot. The improved S-curve acceleration and deceleration algorithm was built based on cubic polynomials for velocity planning. On the basis of ensuring acceleration continuity, five-stage motion planning was used so that the algorithm was easy to implement. Different S-curve transition forms can be selected according to different working conditions. Simulation and experimental results show that the proposed S-shaped acceleration and deceleration control algorithm can effectively reduce the flexible shocks of the system and improve the operation smoothness and control accuracy of the system.

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