An accurate stop control method of high-speed rolling machine for automobile production line using laser ranging and two positon close loop

Zhifeng Qiao¹,²,*, Weimin Ge¹,², Haikang Zhang³, Huiyong Wei³
¹ Tianjin Key Laboratory for Advanced Mechatronic System Design and Intelligent Control, School of Mechanical Engineering, Tianjin University of Technology, Tianjin 300384, China
² National Demonstration Center for Experimental Mechanical and Electrical Engineering Education (Tianjin University of Technology)
³ Automotive Engineering Corporation (AE), NO.591, Changjiang Road, Nankai District, Tianjin, China
* qiaozhifeng@email.tjut.edu.cn

Abstract. The high-speed rolling machine is a key equipment in the automatic production line of automobile body-in-white welding. This article focuses on analyzing a method for accurately stopping the high-speed rolling machine using laser distance measurement. Firstly, through the analysis of the movement process, the calculation method of the length of each period in the 7-stage S-type acceleration and deceleration in the movement of the high-speed rolling machine is given; secondly, the system control theory model of the measurement and control system is established to analyze the dual-position closed-loop strategy. The method of realizing the accurate stopping of the high-speed rolling machine; finally, the accurate stopping control method of the high-speed rolling machine proposed in this paper was verified by building an experimental system and developing the corresponding control program.

1. Introduction
The high-speed rolling machine is a key equipment in the automated production line of automotive body-in-white welding[1-3]. It is mainly responsible for the rapid conveying and accurate stop positioning of the automotive body-in-white. Its performance will directly affect the production cycle and product quality of the production line. In actual production, in order to meet the needs of the production cycle, the maximum speed of the high-speed rolling machine needs to reach 60m/min or more[4,5]. As shown in Fig. 1, the high-speed rolling machine often uses rollers for transportation. Because of rolling friction, it is easy to achieve higher conveying speed. Due to the small friction coefficient, the skid often has slipping during the start and stop stages, that is, the speed between the skid and the roller is often inconsistent.

However, while the skid transports the body-in-white at high speed, it is also required to accurately stop at the positioning point, which requires the electric drive system to take into account both the speed and the positioning accuracy[6]. In motion control, speed and accuracy are contradictory physical quantities, and it is often difficult to balance them. For this reason, this paper proposes a double-position closed-loop accurate stop control method for a high-speed rolling bed that uses laser distance
measurement to accurately measure the sliding displacement, and combines encoder feedback to achieve rough positioning of the rollers.

![Fig. 1 Schematic diagram of a high-speed rolling machine with fast exact stop function](image)

**2. Dynamic performance analysis of high-speed rolling machine transmission system**

**2.1. Mechanical transmission scheme**

As shown in Fig. 2, the high-speed rolling machine with exact stop function mainly consists of:

1. skid, 2. photoelectric switch, 3. conveyor roller, 4. synchronous belt drive system, 5. safety blocking device, 6. laser ranging sensor, 7. motion control and drive system, 8. mechanical frame, 9. reducer, 10. three-phase motor, 11. Encoder.

![Fig. 2 The composition of the high-speed rolling bed conveyor system](image)

**2.2. Motion process analysis and calculation**

Since the weight of the products conveyed by the high-speed rolling machine plus the skid can reach more than 1000KG, the use of traditional trapezoidal acceleration and deceleration is often easy to cause greater mechanical shock during the start-up phase, which will affect the service life of the equipment, so high-speed rolling machines generally need to be used S-shaped movement speed curve. The movement process of a high-speed rolling machine is mainly divided into: acceleration phase, acceleration phase, deceleration phase, uniform speed phase, acceleration and deceleration phase and deceleration phase. For a typical high-speed rolling bed, it is necessary to ensure that the transportation of about 6.5m is completed in the shortest possible time, but also to minimize the mechanical shock in the acceleration and deceleration stage. Therefore, within the allowable range of acceleration, try to shorten the acceleration stage Time, so that it can reach the maximum transmission speed allowed by the motor in the shortest time, so that as much time as possible can be allocated to the deceleration phase, thereby greatly reducing the mechanical impact of the transmission equipment and improving the positioning accuracy of the equipment.

In summary, a reasonable allocation of time in the acceleration phase $T_a$, uniform speed phase $T_u$, and deceleration phase $T_d$ is the focus of the optimal design of the motion process.
Fig. 3 shows a typical S-shaped acceleration and deceleration trajectory of a high-speed rolling machine. The initial speed $v_i = 0$, target speed $v_f$, maximum allowable jerk $J_{\text{max}}$, maximum allowable acceleration $a_{\text{max}}$, end speed $v_e = 0$, initial acceleration and end acceleration are all 0. And under the premise that the sum of the time period $T_2$ and $T_6$ is not 0, the acceleration, velocity and displacement equations for the time period $0 \leq t \leq T_1$ are:

$$a_i(t) = J_{\text{max}} t$$  \hspace{1cm} (1)
$$v_i(t) = \frac{1}{2} J_{\text{max}} t^2$$  \hspace{1cm} (2)
$$s_i(t) = \frac{1}{6} J_{\text{max}} t^3$$  \hspace{1cm} (3)

The acceleration, velocity and displacement equations for the time period $T_i < t \leq T_i + T_2$ are:

$$a_i(t) = J_{\text{max}} T_i$$  \hspace{1cm} (4)
$$v_i(t) = J_{\text{max}} T_i (t - T_i) + \frac{1}{2} J_{\text{max}} T_i^2$$  \hspace{1cm} (5)
$$s_i(t) = \frac{1}{2} J_{\text{max}} T_i (t - T_i)^2 + \frac{1}{2} J_{\text{max}} T_i^2 (t - T_i) + \frac{1}{6} J_{\text{max}} T_i^3$$  \hspace{1cm} (6)

And now there is $a_i(t) = a_{\text{max}}$, so we can get:

$$T_i = \frac{a_{\text{max}}}{J_{\text{max}}}$$  \hspace{1cm} (7)

The acceleration, velocity and displacement equations for the time period $T_i + T_2 < t \leq T_i + T_2 + T_3$ are:

$$a_i(t) = J_{\text{max}} T_i - J_{\text{max}} (t - T_2 - T_i)$$  \hspace{1cm} (8)
$$v_i(t) = -\frac{1}{2} J_{\text{max}} (t - T_i - T_2)^2 + J_{\text{max}} T_i (t - T_i - T_2) + J_{\text{max}} T_2 T_3 + \frac{1}{2} J_{\text{max}} T_3^2$$  \hspace{1cm} (9)
$$s_i(t) = -\frac{1}{6} J_{\text{max}} (t - T_i - T_2)^3 + \frac{1}{2} J_{\text{max}} T_i (t - T_i - T_2)^2 + J_{\text{max}} T_2 T_3 T_i + \frac{1}{2} J_{\text{max}} T_3 T_3 T_i + \frac{1}{6} J_{\text{max}} T_3^3$$  \hspace{1cm} (10)

In addition, generally there will be $T_1 = T_2 = T_3 = T_4$.

For the time period $T_i + T_2 + T_3 < t \leq T_i + T_2 + T_3 + T_4$, the uniform motion stage, the acceleration and velocity equations are:
T_{i} = \begin{cases} T_{i} - T_{i-1} & \text{if } i \text{ is odd} \\ T_{i} + T_{i-1} & \text{if } i \text{ is even} \end{cases}

\begin{align}
\dot{v}_{i}(t) &= \frac{1}{2} J_{\text{max}} T_{i}^{2} + J_{\text{max}} T_{i-1} T_{i} + J_{\text{max}} T_{i} T_{i+1} - \frac{1}{2} J_{\text{max}} T_{i}^{2} \\
T_{v} &:= \max \{1, \max(2, \max(3, 1))\} \\
v_{i}(t) &= J_{\text{max}} T_{i}^{2} + J_{\text{max}} T_{i} T_{i+1} \quad \text{(12)}
\end{align}

In addition, there is generally $T_{i} = T_{i} = T_{i} = T_{i}$, so Eq. (12) can be further simplified as:

\begin{align}
v_{i}(t) &= J_{\text{max}} T_{i}^{2} + J_{\text{max}} T_{i} T_{i+1} \\
T_{v} &:= \max \{1, \max(2, \max(3, 1))\} \\
v_{i}(t) &= J_{\text{max}} T_{i}^{2} + J_{\text{max}} T_{i} T_{i+1} \quad \text{(13)}
\end{align}

Substituting $v_{i}(t) = v_{i}$ into Eq. (14), we can get:

\begin{align}
v_{i} &= J_{\text{max}} T_{i}^{2} + J_{\text{max}} T_{i} T_{i+1} \\
T_{v} &:= \max \{1, \max(2, \max(3, 1))\} \\
v_{i}(t) &= J_{\text{max}} T_{i}^{2} + J_{\text{max}} T_{i} T_{i+1} \quad \text{(14)}
\end{align}

Substituting Eq. (7), we can further obtain:

\begin{align}
T_{i} &= \frac{v_{i}}{a_{\text{max}}}, \quad \frac{a_{\text{max}}}{J_{\text{max}}} \\
T_{v} &:= \max \{1, \max(2, \max(3, 1))\} \\
v_{i}(t) &= J_{\text{max}} T_{i}^{2} + J_{\text{max}} T_{i} T_{i+1} \quad \text{(15)}
\end{align}

From Eq. (7) and Eq. (14), it can be concluded that the time $T_{a}$ required for the acceleration stage in the S-shaped acceleration and deceleration movement of the rolling bed is:

\begin{align}
T_{a} &= T_{1} + T_{2} + T_{2} = \frac{v_{i}}{a_{\text{max}}} + \frac{a_{\text{max}}}{J_{\text{max}}} \\
T_{v} &:= \max \{1, \max(2, \max(3, 1))\} \\
v_{i}(t) &= J_{\text{max}} T_{i}^{2} + J_{\text{max}} T_{i} T_{i+1} \quad \text{(16)}
\end{align}

Assuming that the maximum allowable jerk and maximum allowable acceleration in the acceleration phase and the deceleration phase are the same, it can be seen that:

\begin{align}
T_{a} &= T_{3} + T_{4} + T_{4} = \frac{v_{i}}{a_{\text{max}}} + \frac{a_{\text{max}}}{J_{\text{max}}} \\
T_{v} &:= \max \{1, \max(2, \max(3, 1))\} \\
v_{i}(t) &= J_{\text{max}} T_{i}^{2} + J_{\text{max}} T_{i} T_{i+1} \quad \text{(17)}
\end{align}

Under the premise that the total movement distance $s_{\text{total}}$ required for high-speed rolling is known, the calculation formula for the time period of uniform motion can be further calculated:

\begin{align}
T_{e} &= s_{\text{total}} \cdot 2 \frac{v_{i} (T_{1} + T_{2} + T_{3})}{v_{i}} \\
T_{v} &:= \max \{1, \max(2, \max(3, 1))\} \\
v_{i}(t) &= J_{\text{max}} T_{i}^{2} + J_{\text{max}} T_{i} T_{i+1} \quad \text{(18)}
\end{align}

Through the above solution, the relationship between the length $T_{i}(i = 1, 2, \ldots, 7)$ of each movement period of the high-speed rolling bed and the moving distance $s_{\text{total}}$ of the high-speed rolling sheet, the target movement speed $v_{i}$, the maximum allowable jerk $J_{\text{max}}$ and the maximum allowable acceleration $a_{\text{max}}$ can be obtained, so as to realize the high speed accurate control of the movement time of the roller bed.

3. Scheme design of detection control system

The high-speed rolling bed detection control system with accurate stop function is shown in Fig. 4.

![Fig. 4 High-speed rolling bed detection and control system with accurate stop function](image-url)
3.1. Detection scheme
As the high-speed roller bed inevitably produces relative sliding between the skid and the roller during the conveying process, in order to achieve an accurate stop, a laser rangefinder is used to accurately measure the position of the skid. Since the three-phase motor that drives the rollers to rotate has a rotary encoder, a dual position feedback is formed. Among them, when the skid is outside the measurement range of the laser rangefinder, the rotary encoder will cooperate with the frequency converter to directly participate in the high-speed and real-time S-type acceleration and deceleration control during the start and stop of the three-phase motor. When the skid is within the measurement range of the laser rangefinder, the rotary encoder and the laser rangefinder together form a dual position feedback, which is used for accurate positioning control of the high-speed rolling bed.

3.2. Two-position closed-loop control method
It can be seen from Fig. 4 that the current loop, speed loop and second position loop are still controlled by the inverter, while the first position loop is realized by the control program running on the upper controller. The characteristics of the dual-position closed-loop control method are:

1. The internal motor servo control mode of the inverter does not require major changes, and the classic three-loop control method is still adopted.
2. In the absence of the second position loop, the high-speed rolling machine can still control to achieve S-shaped acceleration and deceleration movement, and can use the in-position switch signal to achieve ordinary stop positioning.
3. The first position ring only needs to work within the set distance range, which can realize the long-distance transportation of the skid.
4. Since the laser ranging sensor is only used for the accurate stop of the last position point, there is no need to accurately calibrate the laser ranging sensor, allowing large installation deviations.

4. Application verification
In order to verify the feasibility of the double-position closed-loop quasi-stop control method of the high-speed rolling machine with S-type acceleration and deceleration, we used the MoviPro series inverter produced by SEW and the DME4000 series laser ranging sensor produced by SICK to build a complete set of high-speed rolling machines. The exact stop function experimental verification platform, the acceleration and deceleration operation of the high-speed rolling bed with two-position closed loop is shown in Fig. 5.

![Fig. 5 High-speed rolling machine running test track with two-position closed loop](image)

In the experiment, the maximum allowable speed of the high-speed rolling bed is 45m/min, the maximum acceleration is 80m/s², and the maximum jerk is 100m/s³. Through the analysis of the
measured trajectory, it can be seen that the high-speed rolling bed can be controlled by the dual position loop. The S-shaped acceleration and deceleration control process is realized relatively smoothly, and the current fluctuation is relatively small, which can ensure accurate positioning and stopping under the feedback of laser ranging.

5. Conclusion
This article focuses on the S-shaped acceleration and deceleration control method and the dual-position closed-loop control strategy closely related to the accurate stopping function of the high-speed rolling machine. The specific calculation formulas for each period of the 7-segment S-shaped acceleration and deceleration are given, which can be convenient for engineers. Reasonably configure the relevant operating parameters of the high-speed rolling machine. The adopted two-position closed-loop control scheme does not require high assembly accuracy of the laser ranging sensor, so it is helpful to upgrade the ordinary high-speed rolling machine. The final experimental results show that the two-position loop exact stop control method using S-type acceleration and deceleration has better control stability.

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