Model Identification and Internal Model Control for 3D Printer

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Abstract. A 3D printer system for selective laser sintering technology is used to establish a mathematical model of the relationship between laser power and temperature by using the recursive least squares method. Based on this model, the internal model control method is used to design the controller to realize the actual 3D printer. Temperature control, simulation analysis of internal model control and traditional PID control effects. The experimental results show that the feasibility, accuracy and internal model control of the recursive least squares identification model are fast, easy to implement, robust, and only one adjustable parameter, easy to adjust.

1. Introduce
Nowadays, 3D printing technology is a technology with potential for development. Pro. Yan, coming from Tsinghua University, has developed the first rapid prototyping equipment in China at that time. At present, PID control is still main control method in 3D printing control systems. This method is based on the model. However the models of industrial processes are often difficult to represent accurately. The accurately modeling of the industrial process has been a precondition of developing the new control methods.

In the paper, the recursive least squares method is used to establish a mathematical model of the laser temperature system.

2. 3D printer system
The paper is focus on SLS (Selective Laser Sintering) technology. Layer-by-layer printing process of the molten metal is completed by the laser scanning of metal powder.

Figure 1. 3D printer physical map
Without considering the error of printer transmission structure, temperature is the most important factor in affecting the accuracy of the modeling. Many characteristics are in printing temperature system, including the temperature rate of change is unstable and it is large inertia and hysteresis. At present, the traditional PID controller is generally used for temperature control. In this method, the overshoot is normal caused and the system stability declined. In the paper, the modeling of laser temperature control is carried out. Internal model controller (IMC) is deployed. It is used in the control system of 3D printing laser power.

3. Temperature Model Identification of 3D Printer Based on Recursive Least Squares

3.1 Model Identification Principle

The input and output of the system to be identified are described as follows:

\[ G(z^{-1}) = B(z^{-1})/A(z^{-1}) \]
\[ A(z^{-1}) = 1 + a_1 \cdot z^{-1} + a_2 \cdot z^{-2} + \ldots + a_n \cdot z^{-n} \]
\[ B(z^{-1}) = b_0 \cdot z^{-n} + b_1 \cdot z^{-n+1} + \ldots + b_m \cdot z^{-n-m} \]  \hspace{1cm} (1)

Where \( G(z^{-1}) \) is the pulse transfer function of the system, \( B(z^{-1}) \) is the numerator of the transfer function, and \( A(z^{-1}) \) is the denominator of the transfer function. Transfer function is converted into the differential form.

\[ z(k) = -a_1 z(k-1) - a_2 z(k-2) - \ldots - a_n z(k-n) + b_0 u(k-1) + b_1 u(k-2) + \ldots + b_m u(k-n-m) + n(k) \]  \hspace{1cm} (2)

Where \( a_1, \ldots, a_n \) is the denominator coefficient, \( n \) is the denominator order; \( b_0, b_1, \ldots \) is the molecular coefficient, \( n_m \) is the molecular order. And \( u(k) \) is the noise interference. \( z(k) \) is the output of system, \( u(k) \) is the stimulant signal of system, and M sequence is generally selected as the input signal. Input-output matrix \( h(k) \) and coefficient matrix \( \theta \) can be constructed. The difference equation can be written as the least squares form:

\[ z(k) = h^T(k) \theta + n(k) \]  \hspace{1cm} (3)

The recursive algorithm is based on the time series. The parameter estimation value is corrected when a new observation data is obtained. And a satisfactory identification result can be obtained finally. Recursive formulas are as follows:

\[ \theta(k) = \theta(k-1) + K(k)[z(k) - h^T(k) \theta(k-1)] \]
\[ K(k) = P(k-1) h(k)[h^T(k) P(k-1) h(k) + \epsilon I]^{-1} \]
\[ P(k) = [I - K(k) h^T(k)] P(k-1) \]  \hspace{1cm} (4)

Where the initial value of \( \theta \), \( \theta(0) = \epsilon I \), is a sufficiently small real number, the initial value of \( P \) is \( P(0) = \alpha^2 I \), \( \alpha^2 \) is a sufficiently large real number.

3.2 3D printer temperature model identification results

Modeling accuracy of physical model is deeply influenced by temperature. The selected model is important for the entire process of the modeling. Most of electric heating systems can be taken as first-order inertia and lag systems. It is used in the 3D printing temperature control system. The expression is

\[ G(s) = \frac{K}{Ts + 1} \cdot e^{-\tau} \]

According to the temperature sample data collected, recursive least squares can be used in model identification of 3D printing. The data collected filtering is carried out. The method of filtering is kalman filtering. The filtered system temperature output curve is shown as...
Figure 2. Printer system output curve

The length of data is about 600 points. The sample time is 0.1s. The processed data is model-identified. About 400 data points are selected for identification. The results are as follows:

Figure 3. The identified system model output comparison

It can be shown in the Figure3. The solid line is the actual system model response curve, and the dotted line is the identified system response curve. The result of fitting is satisfactory. The identified result of the 3D printing model is:

\[ G(s) = \frac{0.896}{1.789s + 1} e^{-3s} \]  

(5)

4. 3D printer temperature internal mode control

For the research of SLS 3D printing temperature control system mentioned, many issues are existing in using the method of traditional PID control. Due to the complex environment of 3D printer, the overshoot and lag will be caused by traditional PID control. The overall stability of the system will be cut down. The workpiece printed cannot fit the requirements. Therefore, IMC is considered.

4.1 Control principle

IMC is based on process model design controller. In fact, it is robust control. The system structure is shown in Figure4.

![Figure 4. Internal model control structure block diagram](image)

\[ G_p(s) \] is the actual object, \( \hat{G}_p(s) \) is the object model, \( R(s) \) is the given value, \( Y(s) \) is the system output, and \( D(s) \) is the disturbance.

4.2 IMC controller design

In factorization process model:
\[ \hat{G}_p = \hat{G}_{p-} \hat{G}_{p+} \]  \hfill (6)

In Eq.5, all the pure time delay and the zero of the right half plane are in \( \hat{G}_{p-} \). And static gain is defined 1. \( \hat{G}_{p-} \) is the minimum phase part of the process model.

In designing of controller:

\[ G_{\text{me}}(s) = \frac{1}{G_{p+}(s)} f(s) \]  \hfill (7)

\( f(s) \) is IMC. The form of the filter needs to be considered. The aim is to ensure that IMC is a proper fraction.

For the step input signal, the form of the Type I IMC filter can be determined:

\[ f(s) = \frac{1}{(T_s s + 1)^r} \]  \hfill (8)

For the ramp input signal, the form of the Type II IMC filter can be determined:

\[ f(s) = \frac{rT_s s + 1}{(T_s s + 1)^r} \]  \hfill (9)

\( T_s \) is the time constant of filter, \( r \) is an integer, and the selection principle is to make \( G_{\text{me}}(s) \) a rational transfer function. It means that the denominator order is not less than the numerator. Therefore, assuming that establishment of mathematical model is accurate. It can be obtained:

\[ \hat{G}_{p-}(s) f(s) \]  \hfill (10)

When \( D(s) = 0 \), there is \( Y(s) = \frac{\hat{G}_{p-}(s) f(s)}{R(s)} \).

It means that the filter \( f(s) \) directly relates to the closed-loop performance. In the filter, the time constant \( T_s \) is an adjustable parameter. The less time constant is, the less \( R(s) \) tracking lag for \( Y(s) \) is. Another effect of the IMC is that the robustness of the system can be adjusted. The larger time constant is, the better robustness is.

5. IMC experiment of 3D printer system

In order to verify the control effect of IMC in 3D printing temperature control system, the comparing of PID and IMC is implemented. The non-minimum phase part of model can be taken:

\[ G(s) = \frac{1.789 s + 1}{0.896} \]  \hfill (11)

In designing of the filter:

For the step input signal, the form of the Type I IMC filter can be determined:

\[ f(s) = \frac{1}{(5s + 1)} \]  \hfill (12)

The filtering parameter \( T_s \) is 5.

In designing of the controller:

\[ G_c(s) = \frac{1.789 s + 1}{0.896} \frac{1}{(5s + 1)} \]  \hfill (13)

According to the controller constructed, the IMC loop is built in Simulink. And PID controller is deployed in the system for comparing the control effect. Experimental simulation results can be obtained. Comparing the control effect through output curves, the result is shown in Figure5.
IMC and PID are used in 3D printing system model. The comparing result can be shown in Figure 5. According to Table 1, the setting of IMC parameter is 5. It can be seen that IMC is faster than PID and the parameter number of IMC is less than PID. The advantage of IMC can be verified including strong stability and easy adjustment. The effect of control can be adjusted by parameter $\tau_f$. The effect of IMC parameter on system response can be shown below.

The characteristic of IMC can be obtained. The larger $\tau_f$ is, the better system robustness is. However the rapidity is reduction. There is only one parameter in IMC. It means that the adjustment process of temperature control is convenience.

6. Conclusion
In this paper, the 3D printing temperature control system is taken as a controlled object. Recursive least squares is used in the system to model identification. The result of identification is satisfactory. IMC is deployed to control 3D printing temperature system. Comparing with the traditional PID control, many advantages are in IMC. Response of system is fast. Robustness is strong. And only one parameter is in IMC, the process of adjusting parameter is not difficult. Superiority of IMC is obvious when the model is difficult to accurate expression. IMC is strong in suppressing process interference. And the robustness and stability can be ensured well in IMC.

Acknowledgements
The work was supported by the grant of National Natural Science Foundation of China (No. 51775430) and Science & Technology Innovation Guidance Project of Xi’an, China (No. 201805037YD15CG21(3)).
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