A Power Optimization Control Method Based on IMC for 3D Printer

Ruidong Xie¹, Haichuan Yang², and Yingmin Yi²∗

¹Key Lab of Manufacturing Equipment of Shaanxi Province, Xi’an University of Technology, Xi’an 710048, China
²Shaanxi Key Laboratory of Complex System Control and Intelligent Information Processing, Xi’an University of Technology, Xi’an 710048, China
∗Corresponding author’s e-mail: yiym@xaut.edu.cn

Abstract. Aiming at the effect of selective laser sintering technology used in 3D printing, the recursive least squares method was applied to fitting a control system model for quantification the relationship between laser power and corresponding temperature in this paper. The internal model control method is considered based on the establishing model. The controller is put into the actual 3D printing power control system for controlling the laser power. In the experiment, both internal model controller and the PID controller for the 3D printer are researched and deployed for comparing the their effects in the paper. The experimental result illustrates that the IMC based on the recursive least squares method is of effectiveness.

1. Introduce
Nowadays, 3D printing in manner of selective laser sintering is a potential technology. Prof. Yan has researched and developed the first additive manufacturing prototype equipment in Tsinghua University China [1]. Currently, PID control has been still the most common control method used in the industrial field. The method relied on the mathematical model of the relationship between power and temperature. However, the mathematical model of controlled object was often hard to be accepted and identify in industry [4-6]. Therefore, how to obtain the accurate model of controlled object has been a precondition for researching the controller design.

In the paper, the method of recursive least squares is applied to identify the physical model between the temperature and power in the laser temperature control system and the internal model control is used to cope with the control issue in the 3D printer power system.

2. 3D printer laser power system
The 3D printing system on SLS (Selective Laser Sintering) is applied as the controlled object, in which layer-by-layer printing technology is used in the laser scanning and sintering over the metal powder. The actual 3D printer is shown in the figure. 1.
Laser sintering temperature is one of the influence factors in deciding the printing accuracy in Additive Manufacturing. Many control difficulties are in 3D printing laser power control system, covering the unstable laser temperature and uneven metal powder. At present, the PID controller as the simple structure is generally used for various kinds of control systems. But in the controller, the response of overshoot is normally existence and the performance is not satisfactory. In this proposed method, the modeling of laser power controller is established by recursive least squares identification. IMC called Internal model controller is set up for controlling the laser power system of 3D printer.

3. Laser Power Model Identification in 3D Printer

3.1. The Principle of Model Identification

The transfer function between setting input and system output in the power control system is shown as follows.

$$G(z^{-1}) = \frac{B(z^{-1})}{A(z^{-1})}$$

$$A(z^{-1}) = 1 + a_1 \cdot z^{-1} + a_2 \cdot z^{-2} + \ldots + a_{n_a} \cdot z^{-n_a}$$

$$B(z^{-1}) = b_1 \cdot z^{-1} + b_2 \cdot z^{-2} + \ldots + b_{n_b} \cdot z^{-n_b}$$

Where $G(z^{-1})$ is used to describe the laser power system, the numerator and the denominator of the function are represented by $B(z^{-1})$ and $A(z^{-1})$ respectively. $n_a$ is the denominator order, $n_b$ is the molecular order. The function is converted into the differential form for calculating as:

$$z(k) = \sum_{i=1}^{n_a} b_i u(k-i) - a_i z(k-i) + n(k)$$

Where $a_i$ is the coefficient about the denominator of the function, $b_i$ is the part about molecular. $z(k)$ is the output of the transfer function, and $u(k)$ is the setting position as the input of the control system. $n(k)$ represents the noise. According to the Eq.(2), the state-transition matrix $h(k)$ and coefficient matrix $\theta$ can be considered for structuring the difference equation. The transfer function can be converted into the least squares form as:

$$z(k) = h^T(k) \theta + n(k)$$

According to the Eq.(3), iterative computations are carried out according to time series. The estimated variables in the recursive function are adjusted when new state data are into the function. And the identification result can be discovered by the algorithm executed repeatedly. Iterative formulas are shown as:
Where the initial value of $\theta_0$ is $\epsilon$ which is an extremely small number. The initial value of $P_0$ is represented as $P_0 = \alpha^2 I$, where $\alpha^2$ is an extremely large number.

3.2. The identification results of the 3D printing power model

The printing accuracy of additive manufacturing is deeply decided by the laser temperature which is related by the laser power. Selecting a suitable mathematical model for controlling is significant for the entire control system of additive manufacturing. Most of controlled objects about temperature can approximately regard as first-order inertia systems with time delay. That is also taken in the 3D printing power controller designing. The general transfer function is $G(s) = \frac{K}{T_s + 1} e^{-\tau s}$.

Using the data captured by the actual 3D printer, the identification method proposed in the above was implemented in identifying the power control model. Kalman Filtering is carried out to filter the temperature data in 3D printer system for preprocessing. The laser temperature curve after smoothing is shown as figure 2.

There are 600 data points in once time series. The sample time is set as 0.1s in the temperature collecting process. After the temperature data preprocessing, there are 400 samples to be selected for identifying the power control system. The identified system is shown as:

4. Internal Mode Controller Designing for 3D Printing Power

As the mentioned power control system, many technological difficulties and unsatisfied effects exist in the control method of PID as the controller for controlling the printer power. Due to the unpredictable
working situation of 3D printing platform and the characteristic of the heating system, the overshoot and time delay will be difficult to cut down by the PID control. The printed workpiece may not meet the requirements of the precision. And IMC is used to cope with those issues.

4.1. Control principle
IMC is a kind of controller design method based on the processing model, which belongs to a kind of robust control. The transfer function structure of system with controller is shown in Figure 4.

![Figure 4. System structure with internal model controller](image)

Where \( G_r(s) \) is the actual laser power control object transfer function, \( \hat{G}_r(s) \) is the prospective object transfer function, \( R(s) \) is the setting temperature, \( Y(s) \) is the output temperature, and \( D(s) \) is the environment noise.

4.2. The design of IMC controller
The factorization process of the transfer function is implemented for controller designing:

\[
P_p = \hat{G}_p \hat{G}_{p_\iota}.
\]

According to Eq. (6), all the pure time delay units and the zero point units in the positive half axis are assigned to \( \hat{G}_{p_\iota} \), in which the gains are defined as unit values. \( \hat{G}_{p_\iota} \) represents the minimum phase of the transfer function.

In the part of controller designing:

\[
G_{\text{imc}}(s) = \frac{1}{G_{p_\iota}(s)} f(s)
\]

(7)

\( f(s) \) represents the IMC filter for adjusting the 3D printer power control system. The form of the filter needs to assure that \( G_{\text{imc}}(s) \) is a proper fraction.

For the step signal as the input of the power control system, the Type-I IMC filter can be designed as:

\[
f(s) = \frac{1}{(T_f s + 1)^r}
\]

(8)

For the ramp signal as the input of the power control system, the Type-II IMC filter can be designed as:

\[
f(s) = \frac{rT_f s + 1}{(T_f s + 1)^r}
\]

(9)

Where \( T_f \) is the time constant in \( f(s) \), \( r \) must be an integer, and it is used to adjust the fraction \( G_{\text{imc}}(s) \) to a expected transfer function. That means the order of the denominator must be higher than the numerator’s. Assuming that the identification model of the controlled object is exactly accurate, it can be obtained:

\[
Y(s) = \hat{G}_{p_\iota}(s) f(s) R(s) + [1 - f(s) \hat{G}_{p_\iota}(s)] D(s)
\]

(10)

Assuming \( D(s) = 0 \), there is

\[
\frac{Y(s)}{R(s)} = \hat{G}_{p_\iota}(s) f(s).
\]

The filter \( f(s) \) directly effects the closed-loop performance of the control object. In the designed
5. Experiment for 3D Printing Power Control System

For verifying the IMC controller advantages in 3D printing power control system, performances between IMC and PID are compared with an actual 3D printing experiment platform. A transfer function of the controlled object as a test can be shown:

\[ G(s) = \frac{1.854s + 1}{0.975} \]

In the part of designing of the filter:

As the above Eq. (8), Type-I IMC filter can be set for the step input signal:

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

Where \( T_f = 5 \).

The controller designed as:

\[ G_{\text{IMC}}(s) = \frac{1.854s + 1}{0.975} \frac{1}{(5s + 1)} \]

According to Eq. (13), the IMC controller is found in Simulink. PID controller as a comparing controller is also found in the system. The comparing result in performance can be obtained after simulating. The result is shown in Figure 5. And the parameters of PID and IMC are listed in Table 1.

![Figure 5. Response of the system over IMC and PID](image)

| Controller | Parameters |
|------------|------------|
| PID        | P | I | D |
|            | 0.001 | 0.1 | 0 |
| IMC        | \( T_f \) | \( f_T \) |
|            | 5    | |

Both of PID controller and IMC controller are found in power control system. The result can be shown in Figure 5. It can obviously discovers in the figure and table that IMC is rapider than PID in the system response, and the parameters to be adjusted in IMC are less than those in PID. The advantages of IMC can be discovered in response and adjustment. The performance of system response can be adjusted by \( T_f \) in the control method of IMC. The way of effect can be shown as follow.
The larger $T_f$ will be in favor of the system robustness. Meanwhile, the speed of response is reduction. However, comparing with the PID controller, there is just one parameter needed to be adjusted in IMC controller so that it is not difficult to apply to engineering.

6. Conclusion
The power control system in 3D printing is regarded as a controlled object in this paper. The method of Recursive least squares is considered to identify the relationship between the power and the temperature in the 3D printing laser power system. The controller of IMC is designed for improving performance of the 3D printing power control system. And comparing with the control method of PID, the superiority can embody in IMC controller, such as robustness and easy to adjust. The advantage of IMC is also obviously discovered when the transfer function of the controlled object is difficult to obtain.

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)) and in part by Key R & D plan of Shaanxi Province(2020ZDLGY06-01).

References
[1] A G H, A W A K, A H A A, et al. Design and development of a lightweight SLS 3D printer with a controlled heating mechanism: Part A[J]. International Journal of Lightwght Materials and Manufacture, 2019, 2(4):373-378.
[2] Mikoajewska E, Macko M, Ziarnecki U, et al. 3D printing technologies in rehabilitation engineering[J]. Journal of Healthences, 2014, 4(12):78-83.
[3] Y. Xiao, J. Yang, Q. Feng, K. Huang, H. Zhou, J. Hu, S. Dong Three-dimensional graphene-based materials by direct ink writing method for lightweight Application Int. J. Lightweight Mater. Manuf., 2 (1) (2018), 96-101.
[4] Roach D J, Hamel C M, Dunn C K, et al. The m 4 3D printer: A multi-material multi-method additive manufacturing platform for future 3D printed structures [J]. Additive Manufacturing, 29, 2019,100819, ISSN 2214-8604.
[5] Rupp D, Guzzella L. Adaptive internal model control with application to fueling control [J]. Control Engineering Practice, 2010, 18(8):873-881.
[6] Qi-Feng P, Wen-Bo L, University Z M. The Application of 3D Printing Technology in Rehabilitation Engineering [J]. Chinese Manipulation & Rehabilitation Medicine, 2018.
[7] Vermeiren L, Guerra T M, Lamara H. Application of practical fuzzy arithmetic to fuzzy internal model control [J]. Engineering Applications of Artificial Intelligence, 2011, 24(6):1006-1017.
[8] Darby M L, Nikolau M. Identification test design for multivariable model-based control: An industrial perspective [J]. Control Engineering Practice, 2014, 22:165-180.
[9] Zeng W, Zhu W, Hui T, et al. An IMC-PID controller with Particle Swarm Optimization algorithm for MSBR core power control [J]. Nuclear Engineering and Design, 360.

[10] Vermeiren L, Guerra T M, Lamara H. Application of practical fuzzy arithmetic to fuzzy internal model control [J]. Engineering Applications of Artificial Intelligence, 2011, 24(6):1006-1017.