Analytical optimization of IMC-PID design based on performance/robustness tradeoff tuning strategy for the modified Smith structure

Liu Li-Ye¹,² and Jin Qi-Bing²

Abstract
In this paper, a modified two degrees of freedom Smith control structure is proposed to realize tradeoff tuning strategy between the dynamic performance and system robustness based on analytical optimization of internal model control proportion integration differentiation design method. By analyzing the stability performance of the modified Smith control structure, the control characteristic between the modified Smith control structure and two adjustment parameters is obtained. The different input responses are discussed based on the performance of modified control system. Moreover, the set point response and the disturbance response of the closed-loop system are adjusted by two parameters, respectively. The multiplicative uncertainty plant is imposed into the modified Smith control system to analyze the system robustness from the aspect of the structure uncertainty. The proposed control strategy is applied to the second order plus delay time plant. The simulation result reflects that the modified Smith control structure is the method which is based on the tradeoff between the performance and the robustness tuning strategy.

Keywords
Second order plus delay time, two degree of freedom, internal model control proportion integration differentiation, Smith control, robustness

Introduction
Model error of the controlled plant and long delay time are widely existing problems in the chemical process, and it is important to handle such issues in the chemical process. A closer control method of the loops with dead time was proposed by Smith¹ to solve the long delay time in the chemical process, which is called Smith predictive control. A general structure for Smith control system is shown in Figure 1.

Recently, lots of researchers put more focus on the Smith predictive control to boost the rapid development of the chemical process control technology. Huang et al.² made an extension of the modified Smith fuzzy PID controller into an oil-replenishing device of the deep-sea hydraulic system to control the temperature. Araújo et al.³ combined the filtered Smith predictors with the receptance of a vibrating system to the design the feedback control for SOPDT plant. However, their approach is short for guaranteeing the stability. Bonala et al.⁴ improved the robustness performance of the networked control systems by a digital Smith predictor with the delay compensator. Lyapunov stability condition is used to prove the stability of the networked control systems. To control unstable and integrating processes with large time delay, Raja and Ali⁵ utilized a modified parallel cascade Smith

¹College of Electrical and Electronic Engineering, Shi Jiazhua University of Applied Technology, Shi Jiazhua, PR China
²Information Science and Technology College, Beijing University of Chemical and Technology, Beijing, China

Corresponding author:
Liu Li-Ye, Shi Jiazhua University of Applied Technology, Shi Jiazhua, Hebei 050081, China.
Email: liuliye@sjzpt.edu.cn

Creative Commons CC BY: This article is distributed under the terms of the Creative Commons Attribution 4.0 License (http://www.creativecmons.org/licenses/by/4.0/) which permits any use, reproduction and distribution of the work without further permission provided the original work is attributed as specified on the SAGE and Open Access pages (https://us.sagepub.com/en-us/nam/open-access-at-sage).
predictor with a secondary disturbance rejection controller into improvement in closed-loop performance. Smith predictive control is also applied to many other areas, for instance, industrial network control,6,7 multiagent formation control,8 directional drilling,9 robot,10 etc.

Internal model control (IMC)11 technology is an important control theory originated for the improvement of Smith predictive control, especially for the large dead time process. Hilsch et al.12 extended IMC structure into nonlinear input saturation systems with the aim to cope with input magnitude constraints. Yadav and Gaur13 proposed a method which combined the fuzzy supervisor and the modified IMC as an adaptive tuning to control the speed of nonlinear uncertain heavy duty vehicle (HDV) through angular position of throttle valve. Kim et al.14 presented a design procedure, which combined nonlinear IMC with linear matrix inequality feasibility to control the stable Wiener system. Bouzid et al.15 proposed a novel nonlinear IMC method for the unmanned aerial vehicle to raise the performance and the robustness level. At current, the innovative application of IMC theory is ongoing.16–18

The 2DOF control structure is also paid close attention by lots of researchers. Singh et al.19 presented a controller design method of the 2DOF-IMC-PID, which combined with model order reduction technique to control directly full order system model. However, they just only made a comparative study of conventional PID and IMC-PID. The described approach is short of analyzing robustness. Zhang et al.20 proposed a 2DOF method of Smith predictor for the first order plus delay time (FOPDT) processes. Smith control system with compensator structure restricts attention to an FOPDT system for the sake of clarity of exposition. There are some deficiencies in this control strategy. For example, the system stability depends on the model of the controlled plant; the equivalent control structure is open control; although the control structure is a 2DOF, they do not consider the analytical optimization based on performance/robustness tradeoff tuning strategy when tuned to the controller parameter.

In this work, it is aimed to enhance the robustness performance of Smith control system for SOPDT process based on the performance/robustness tradeoff tuning. A modified TDF Smith control structure is proposed to overcome the above deficiencies based on analytical optimization of IMC-PID design method with considering the tradeoff tuning strategy between the dynamic performance and system robustness.

Stability performance of modified Smith structure

In the chemical process, the FOPDT model and the SOPDT widely existed. Meanwhile, the higher order plant can be induced into FOPDT in the process of analyzing the system and designing the controller. Then, the induced order error is seen as the internal error in the design process. In the induced order process, the middle–low frequency character of FOPDT coincides with that of the higher order plant. Therefore, SOPDT plant has been chosen to be applied in the modified 2DOF control method. In the chemical process, the structure of the controlled plant is stable and the parameters of the controlled plant are generally uncertain. Thus, the structure of SOPDT plant with the uncertainty parameters is adopted as the research plant. It is significant for the proposed control strategy to extend into the higher order plant. Modified structure for Smith control system with feedback structure is shown in Figure 2. In Figure 2, the controlled plant $G(s)$ is considered as SOPDT, as shown in equation (1)

$$G(s) = \frac{k}{\omega_1 s^2 + \omega_2 s + 1} e^{-\theta s}$$

Remark 1: Most of high-order system in the chemical process can be reduced into a SOPDT system. The proposed method can be extended into higher order systems. However, the reduction error must be considered into the influence of the system robustness when tunes the controller parameters.
According to the IMC control theory,\textsuperscript{11} the corresponding IMC controller is given by the following equations.

\[
G_{IMC}(s) = \frac{\omega_1 s^2 + \omega_2 s + 1}{k (\lambda_1 s + 1)^3} \quad (2)
\]

\[
G_C(s) = \frac{G_{IMC}(s)}{1 + G_{IMC}(s)G(s)} = \frac{(\beta s + 1)(\omega_1 s^2 + \omega_2 s + 1)}{k (\lambda_1 s + 1)^3 - k (\beta s + 1)e^{-\alpha s}} \quad (3)
\]

where \( \beta = T [1 - \left( \frac{\alpha}{T} - 1 \right)^2 e^{-\frac{\pi}{T}}] \), \( \alpha = \alpha \lambda_1 \).

\[
y(s) = \frac{G_C(s)G(s)}{1 + G_C(s)G(s)} r(s) + \frac{d(s)G(s)}{1 + G_C(s)G(s)} - \frac{d_m(s)G(s)}{1 + G_C(s)G(s)} \quad (4)
\]

**Remark 2**: the external disturbance \( d(s) \) is a bounded signal and satisfies \( \lim_{t \to \infty} d(t) = \lim_{t \to \infty} s d(s) < \infty \).

Therefore, the input error of the modified Smith control strategy is obtained by the following equation.

\[
e_r(s) = \frac{G_C(s)G(s)}{1 + G_C(s)G(s)} r(s) - r(s) \quad (5)
\]

According to the robust control theory,\textsuperscript{21} the sensitivity function, which reflects the robustness of control system, can be obtained by the following equation.

\[
S = \frac{1}{1 + G_C(s)G(s)}, \quad T = \frac{G_C(s)G(s)}{1 + G_C(s)G(s)} \quad (6)
\]

Where \( SG_C(s)G(s) - 1 = T - 1 = -S \).

Substituting equation (6) into equation (5), the following equation can be obtained.

\[
e_r(s) = -Sr(s) = (T - 1)r(s) \quad (7)
\]

It is known from equation (7) that \( e_r(s) \) is proportional to \( S \). Thus, when the input signal \( r(s) \) is known, if it is desired to obtain the minimum value of \( e_r(s) \), the sensitivity function \( S \) should be minimized.

And then, the disturbance input error of the modified Smith control strategy is obtained by the following equation.

\[
e_d(s) = d(s) - \frac{d(s)G(s)}{1 + G_C(s)G(s)} - \frac{d_m(s)G(s)}{1 + G_C(s)G(s)} - d(s) = \frac{G(s)}{1 + G_C(s)G(s)} [d(s) - d_m(s)] - d(s) \quad (8)
\]
From the above equation, it is obvious that $e_d(s)$ is the minimum value when the external disturbance signal is equal to the internal disturbance signal ($d(s) = d_m(s)$).

**Modified structure for $M(s)$**

As shown in Figure 3, the expression of $M(s)$ and $v(s)$ is obtained in the following equations

$$M(s) = \frac{(\omega_1 s^2 + \omega_2 s + 1)M_0(s)}{1 - (\omega_1 s^2 + \omega_2 s + 1)M_0(s)G(s)}$$

(9)

$$v(s) = \frac{[d(s) - d_m(s)]G(s)[1 + G_C(s)G_m(s)]}{1 + G_C(s)G(s)}$$

(10)

Assuming that the system model matches, $G_m(s) = G(s)$, then the following equations can be derived

$$v(s) = [d(s) - d_m(s)]G(s)$$

(11)

$$v_0(s) = d_m(s)G_m(s) + [d(s) - d_m(s)]G(s) = d(s)G(s)$$

(12)

$$d_m(s) = v_0(s)M_0(s)(\omega_1 s^2 + \omega_2 s + 1) = d(s)ke^{-\theta s}M_0(s)$$

(13)

Equation (13) shows that the equivalent structure $M(s)$ is an estimator, which can estimate the external disturbance. According to equation (8), $e_d(s)$ is the minimum value when the external disturbance signal is equal to the internal disturbance signal ($d(s) = d_m(s)$). Therefore, the constraint condition should be satisfied as follows

$$\lim_{s \to 0} [d(s) - d_m(s)] = 0$$

(14)

Substituting equation (15) into equation (16), the following equations can be obtained

$$\lim_{s \to 0} [1 - ke^{-\theta s}M_0(s)]d(s) = 0$$

(15)

$$\lim_{s \to 0} ke^{-\theta s}M_0(0) = 1$$

(16)

Thus, Following the Final Value Theorem (FVT), $M_0(s)$ must satisfy the following constraint condition

$$\lim_{s \to 0} M_0(0) = \frac{1}{k}$$

(17)

Thus, the following conditions must be satisfied by $M_0(s)$

$$M_0(s) = \frac{1}{k(\lambda_2 s + 1)^2} \text{ or } M_0(s) = \frac{\rho s + 1}{k(\lambda_2 s + 1)^2}$$

(18)
Remark 3: $k_2$ is a regular parameter, $\rho = \kappa k_2$, which is adjustable to obtain the desired capability of disturbance rejection.

Simplified modified Smith control structure

The disturbance response can be obtained as follows

$$y_d(s) = \frac{(\lambda_1^3s + 1)^3 - (\beta s + 1)e^{-\theta s}}{(\lambda_1 s + 1)^3} G(s)(1 - ke^{-\theta s}M_0(s))d(s) \quad (19)$$

Assume

$$y_d(s) = \chi(s)\psi(s) \quad (20)$$

where $\chi(s) = \frac{(\lambda_1 s + 1)^3 - (\beta s + 1)e^{-\theta s}}{(\lambda_1 s + 1)^3} G(s)$, $\psi(s) = (1 - ke^{-\theta s}M_0(s))d(s)$ and $\chi(s)$ and $\psi(s)$ has the steady-state values.

According to equation (19), the modified structure of Smith predictive control can be simplified as shown in Figure 4.

Remark 4: In the chemical process, in general, the output physical quantity is the temperature, pressure and liquid. And then, the input physical quantity is the valve, including solenoid, magnetic. In order to research the universality and the feasibility of the proposed control strategy, the step response is adopted to the system input in this paper, which is usually considered as the system input by most of researchers.

Design controller

The adjustable parameter $\lambda_1$ reflects the tradeoff between the system performance and robustness. The adjustable parameter $\lambda_2$ reflects the capability of the disturbance rejection of the Smith control strategy. The tuned process of the adjustable parameter $\lambda_1$ and $\lambda_2$ are shown in Figure 5.

Tuning the parameter $\lambda_1$

Substituting equations (1) and (3) into equation (6), the following equation is derived

$$S = 1 - \frac{(\beta s + 1)e^{-\theta s}}{(\lambda_1 s + 1)^3} \quad (21)$$

For the time delay plant, it is handled by Taylor series expansion method, as shown in equation (22).

$$e^{-\theta s} \approx 1 - \theta s$$

(22)
By expanding equation (21), the following equation can be obtained

\[
S = \frac{\lambda_1 s^3 + (3\lambda_1 - \beta \theta) s^2 + (3\lambda_1 - \beta + \theta) s}{\lambda_1 s^3 + 3\lambda_1^2 s^2 + 3\lambda_1 s + 1}
\] (23)

**Remark 4:** Because of the existence of the delay time constant \( \theta \), it is complex to analyze the sensitivity function. Thus, equation (23) has to make change of scale, as shown in equation (24).

\[
S = \frac{\mu^3 \delta^3 + (3\mu^2 - \varepsilon) \delta^2 + (3\mu - \varepsilon + 1) \delta}{\mu^3 \delta^3 + 3\mu^2 \delta^2 + 3\mu \delta + 1}
\] (24)

where

\[
\mu = \frac{\lambda_1}{\theta}, \quad \varepsilon = \frac{\beta}{\theta}, \quad s = \frac{\delta}{\theta}
\] (25)

In the frequency scope of \( 0 < \omega < \infty \), the maximum sensitivity function \( M_s \) can be derived as the following expression

\[
M_s = \max_{0 < \omega < \infty} \left| \frac{\mu^3 \delta^3 + (3\mu^2 - \varepsilon) \delta^2 + (3\mu - \varepsilon + 1) \delta}{\mu^3 \delta^3 + 3\mu^2 \delta^2 + 3\mu \delta + 1} \right|
\] (26)
The different relationship curves between $M_s$ and $\mu$ can be obtained in the different values of $\alpha$, as shown in Figure 6.

Integral absolute error (IAE) value is an important index for the stability performance of the control system. From the aspect of computation amount, IAE has decreased complexity for the proposed method when compared to other methods. Thus, the authors choose the IAE as the research index. However, the tuning of the objective function is not limited on IAE. This will be investigated in future researches.

According to the definition of IAE, the step response is imposed on the input, and the following equation can be obtained

$$IAE_r = \int_0^\infty |y_r(t) - r(t)| dt = \int_0^\infty t^{-1} \left[ \frac{1}{s} (1 - \frac{(\beta s + 1)e^{-\delta s}}{s(\lambda_1 s + 1)^3}) \right] dt$$

(27)

Calculating the equation and resulting in the following equation

$$IAE_r = \begin{cases} t & \text{if } t \leq \theta \\ \frac{t}{3\lambda_1 - \beta + \theta} & \text{if } t > \theta \end{cases}$$

(28)

When $t > \theta$, the result is simplified by $IAE_r' = (3 - \alpha)\mu + 1$, where $IAE_r' = \frac{IAE_r}{\mu} \approx \alpha$.

The typical PID controller is shown in equation (29)

$$C_i(s) = K_m \left( 1 + \frac{1}{T_is} + T_ds \right)$$

(29)
Expanding equation (3) in a Maclaurin series with $s$, compared with the equation (29) by the coefficient, the parameters of PID controller are calculated by the following equation

$$
\begin{align*}
KC &= \frac{(3\lambda_1 - \beta + \theta)\omega_2 + 3\lambda_1^2 - \frac{1}{2}\theta^2 + \beta\theta}{k(3\lambda_1^2 - \beta + \theta)^2} \\
TI &= \frac{(3\lambda_1 - \beta + \theta)\omega_2 + 3\lambda_1^2 - \frac{1}{2}\theta^2 + \beta\theta}{k(3\lambda_1^2 - \beta + \theta)} \\
TD &= \frac{k(\omega_2 - \omega_1)(3\lambda_1 - \beta + \theta) - k\omega_2(3\lambda_1^2 - \frac{1}{2}\theta^2 + \beta\theta) + k\left(\lambda_1^2 - \frac{1}{6}(3\beta\theta^2 - \theta^3)\right)}{-k(3\lambda_1 - \beta + \theta) + k(3\lambda_1^2 - \frac{1}{2}\theta^2 + \beta\theta)} + TI
\end{align*}
$$

(30)

**Tuning the parameter $\lambda_2$**

According to the definition of IAE, the step response is imposed on the disturbance terminal, and the following equation can be obtained

$$
IAE_d = \int_0^\infty |y_d(t) - d(t)|\,dt = \int_0^\infty \left|e^{-1}\left\{1 - G(s) \frac{1}{1 + G(s)G(s)(1 - ke^{-\theta s}M_0(s)) - 1}\right\}\right|\,dt
$$

(31)

Assume that

$$
IAE_{dq} = \int_0^\infty \left|e^{-1}\left\{1 - ke^{-\theta s}M_0(s)\right\}\right|\,dt
$$

(32)

According to equation (32), if $IAE_d' \to 0$, $IAE_{dq}' \to 0$, then $IAE_d \to D(s)$.

Substituting equation (18) into equation (32), this following equation can be obtained

$$
IAE_d' = \int_0^\infty \left|e^{-1}\left\{1 - \frac{ps + 1}{(\lambda_2^2 s + 1)^2}e^{-\theta s}\right\}\right|\,dt
$$

(33)

Calculating the equation and changing the scale, we get the following

$$
IAE_{dq} = \begin{cases} 
    t & t \leq \theta \\
    2\lambda_2 + \theta - t & t > \theta
\end{cases}
$$

(34)

where $\rho = \kappa\lambda_2$. It is obviously that the error between the disturbance and the output is maximum when $\lambda_2 = -\frac{\theta}{2}$ and $\rho = 0$.

**Robustness analysis**

To analyze the system robustness, the multiplicative uncertainty plant is imposed into the control system, as shown in Figure 7. The following equation is obtained from Figure 7

$$
L_p(s) = G(s)G_c(s)[1 + \omega_l(s)\Delta_l(s)]
$$

(35)

where, $|\Delta_l(j\omega)| \leq 1, \forall \omega$. 
Let
\[ L(s) = G(s)G_c(s) = \frac{(\beta s + 1)e^{-\theta s}}{\lambda_1 s + 1 - k(\beta s + 1)e^{-\theta s}} \]  
(36)

Then the complementary sensitivity function is given by the following equation
\[ T(s) = \frac{L(s)}{1 + L(s)} = \frac{(\beta s + 1)e^{-\theta s}}{\lambda_1 s + 1 - k(\beta s + 1)e^{-\theta s} + (\beta s + 1)e^{-\theta s}} \]  
(37)

Expanding equation (35), the following equation can be obtained
\[ L_p(s) = L(s) + \omega I(s)L(s)\Delta I(s) \]  
(38)

According to the Nyquist stability criterion,\(^\text{23}\) the robust stability condition of the modified Smith control system is that if the system is stable, the Nyquist curve of \(L_p(s)\) should not encircle the point \((-1, j0)\) in the complex plane. Thus, the following equation can be derived as follows
\[ |\omega I(j\omega)T(j\omega)| = \frac{|\omega I(j\omega)L(j\omega)|}{1 + L(j\omega)} < 1 \forall \omega \]  
(39)

Furthermore, the robust stability condition of the modified Smith control system is shown in equation (40).
\[ \left|\frac{(j\beta w + 1)e^{-j\theta w}}{(j\lambda_1 w + 1)^3 - k(j\beta w + 1)e^{-j\theta w} + (j\beta w + 1)e^{-j\theta w}}\right| < \frac{1}{\omega I(j\omega)}, \quad \forall \omega \]  
(40)

**Illustration**

In this paper, SOPDT plant is chosen as the control plant to verify the effectiveness of the proposed method. The transform function of the controlled plant is given by the following equation
\[ G(s) = \frac{5}{50s^2 + 15s + 1}e^{-s} \]

According to the section of design controller, the internal model controller and the equivalent the feedback controller can be obtained by the following equation
\[ G_{IMC}(s) = \frac{(\beta s + 1)(50s^2 + 15s + 1)}{5(\lambda_1 s + 1)^3}, \quad G_c(s) = \frac{(\beta s + 1)(50s^2 + 15s + 1)}{5(\lambda_1 s + 1)^3 - 5(\beta s + 1)e^{-s}} \]
The disturbance estimator is given by the following equation

\[ M_0(s) = \frac{\rho s + 1}{5 \times (\lambda_2 s + 1)^3} \]

Figure 8. Relationships among the PID coefficients and \( \lambda_1 \).

Figure 9. Relationships between \( IAE_{dq} \) and \( \lambda_2 \).

The disturbance estimator is given by the following equation

\[ M_0(s) = \frac{\rho s + 1}{5 \times (\lambda_2 s + 1)^3} \]
Figure 10. Output of set point response for modified Smith control structure. IMC: internal model control; 2DOF: two degrees of freedom.

Figure 11. Control law of set point response for modified Smith control structure. IMC: internal model control; 2DOF: two degrees of freedom.
The proposed method is used to tuning the parameters $\lambda_1$ and $\lambda_2$. According to equation (30), the expression of parameters of PID controller, the relationships among the PID coefficients and $\lambda_1$ are obtained, as shown in Figure 8. According to equation (34), the relationships between $\lambda_2$ and $\lambda_1$ are obtained, as shown in Figure 9.

To evaluate the performance of the modified Smith control system in the time domain, a unit step response is imposed on the input terminal at 5 s, and a step load disturbance is imposed on the output terminal at 60 s. The proposed method is compared with Simped Internal Model Controller (SIMC)\textsuperscript{24} and IMC-Mac.\textsuperscript{25} The output of the set point response and the control law of the set point response for the modified Smith control structure are shown in Figures 10 and 11, respectively. Figures 10 and 11 prove the validity that the modified Smith control structure is based on the tradeoff between the performance and the robustness tuning strategy. The performance of the set point response for the example is shown in Table 1.

To estimate the performance of the modified Smith control system in the frequency domain, the frequency responses from the input terminal to the output terminal, including impulse response, Nyquist diagram, Bode diagram and Nichols Chart, are shown in Figure 12, and then Figure 13 shows the frequency responses from the input terminal to the output terminal. It is obvious from Figures 12 and 13 that the modified Smith structure has

### Table 1. The performance of the set point response for the examples.

| Example   | Method     | IAE (Set point response) | Overshoot (%) | IAE (Load disturbance) | Overshoot (%) |
|-----------|------------|--------------------------|---------------|------------------------|---------------|
| SOPDT     | SIMC       | 0.73                     | 5.36          | 0.11                   | 20.13         |
| SOPDT     | IMC-Mac    | 0.91                     | 0             | 0.08                   | 19.37         |
| SOPDT     | Proposed   | 0.41                     | 0             | 0.03                   | 13.28         |

IAE: integral absolute error value; IMC: internal model control; SOPDT: second order plus delay time.
Figure 13. Frequency response of disturbance input terminal for modified Smith control structure. IMC: internal model control; 2DOF: two degrees of freedom.

Figure 14. Step disturbances for modified Smith control structure. IMC: internal model control; 2DOF: two degrees of freedom.
good dynamic performance in the frequency domain. Especially, Nyquist curves of the modified Smith structure do not encircle the point \((-1, j0)\) in the complex plane.

To evaluate the disturbance rejection performance of the modified Smith control system in the different types of the disturbance, the step disturbance and the white noise are imposed on the disturbance input terminal. At the disturbance input terminal, the gain of the step disturbance increases two times and the delay time of the step disturbance increases 20%, as shown in Figure 14. Figure 15 shows the capability of the anti-disturbance for the modified Smith control system when the white noise disturbance is imposed on the disturbance input terminal.

It is known from Figures 10 to 15 that the proposed Smith control structure has the strong capability of the dynamic characteristic and the disturbance rejection. Compared with other two methods, control effectiveness of the proposed method is similar to IMC-MAC and better than SIMCs. Moreover, the capability of the anti-disturbance of the modified Smith control structure is obviously better than the other two methods. However, the proposed method is not perfect. For example, the part of the performance index of the modified Smith control structure is not optimal, including rise time, overshoot, etc. The simulation result also reflects that the proposed Smith control structure is the method which is based on the tuning tradeoff between the performance and the robustness tuning strategy.

**Conclusion**

A modified 2DOF Smith control structure is described. It is used to realize tradeoff tuning strategy between the dynamic performance and system robustness based on analytical optimization of IMC-PID design method. The proposed control strategy is applied to SOPDT plant. Illustration process shows that the proposed Smith control structure has the strong capability of the dynamic characteristic and the disturbance rejection. The strong efficiency of the approach we have proposed here has demonstrated that the proposed Smith control structure is the method which is based on the tradeoff between the performance and the robustness tuning strategy. However, the proposed method is not perfect. Several issues are still under research. For example, the system robustness of the proposed control strategy is just only considered on the structure multiplicative uncertainty aspect. Further research extending the presented methodology to the controller design for the nonlinear plant with large model errors is currently ongoing.
Acknowledgements

The authors are grateful to the anonymous reviewers for their valuable recommendations.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The authors would like to acknowledge the financial support of the National Natural Foundation of China (61473024) and higher school specialized research fund for the doctoral program (16YB1001).

ORCID iD

Liu Li-Ye http://orcid.org/0000-0002-4522-525X

Reference

1. Smith JM. Closer control of loops with dead time. Chem Eng Progr 1957; 53: 217–219.
2. Huang H, Zhang S, Yang Z, et al. Modified Smith fuzzy PID temperature control in an oil-replenishing device for deep-sea hydraulic system. Ocean Eng 2018; 149: 14–22.
3. Araújo J and Santos T. Control of a class of second-order linear vibrating systems with time-delay: Smith predictor approach. Mech Syst Signal Process 2018; 108: 173–187.
4. Bonala S, Subudhi B and Ghosh S. On delay robustness improvement using digital Smith predictor for networked control systems. Eur J Control 2017; 34: 59–65.
5. Raja G and Ali A. Smith predictor based parallel cascade control strategy for unstable and integrating processes with large time delay. J Process Control 2017; 52: 57–65.
6. Batista A and Jota F. Performance improvement of an NCS closed over the internet with an adaptive Smith Predictor. Control Eng Pract 2018; 71: 34–43.
7. Gamal M, Sadek N, Rizk M, et al. Delay compensation using Smith predictor for wireless network control system. Alexandria Eng J 2016; 55: 1421–1428.
8. González A, Aranda M, Nicolás G, et al. Time delay compensation based on Smith Predictor in multiagent for motion control. Int Federation Autom Control 2017; 50: 11645–11651.
9. Inyang I and Whidborne J. Applying a modified Smith predictor-bilinear proportional plus integral control for directional drilling. Int Federation Autom Control 2017; 50: 139–144.
10. Aguirre A, Villa M and Cuellar B. Nonlinear Smith-predictor based control strategy for a unicycle mobile robot subject to transport delay. In: International conference on electrical engineering, computing science and automatic control, Mexico, 11–14 November 2008. Piscataway, NJ: IEEE, pp.102–107.
11. Garcia C and Morari M. Internal model control-I. A unifying review and some new results. Ind Eng Chem Proc Des Dev 1982; 21: 308–323.
12. Hilsch M, Lunze J and Nitsche R. Internal model control of nonlinear systems with input saturation. Automatisierungstechnik 2011; 59: 354–363.
13. Yadav A and Gaur P. Intelligent modified internal model control for speed control of nonlinear uncertain heavy duty vehicles. ISA Trans 2015; 56: 288–298.
14. Kim K, Patrónc E and Braatz R. Robust nonlinear internal model control of stable Wiener systems. J Process Control 2012; 22: 1468–1477.
15. Bouzid Y, Siguerdidjane H and Bestaoui Y. Nonlinear internal model control applied to VTOL multi-rotors UAV. Mechatronics 2017; 47: 49–66.
16. Jin Q, Du X and Jiang B. Novel centralized IMC-PID controller design for multivariable processes with multiple time delays. Ind Eng Chem Res 2017; 56: 4431–4445.
17. Jin Q, Wang Q and Liu L. Design of decentralized proportional integral derivative controller based on decoupler matrix for two-input/two-output process with active disturbance rejection structure. Adv Mech Eng 2016; 8: 1–16.
18. Jin Q and Liu L. Design of active disturbance rejection internal model control strategy for SISO system with time delay process. J Cent South Univ 2015; 22: 1725–1736.
19. Singh J, Chattterjee K and Vishwakarma C. Two degree of freedom internal model control-PID design for LFC of power systems via logarithmic approximations. ISA Trans 2018; 72: 185–196.
20. Zhang W, Sun Y and Xu X. Two degree-of-freedom Smith predictor for processes with time delay. *Automatica* 1998; 34: 1279–1282.

21. Francis B and Khargonekar P. *Robust control theory*. New York: Springer-Verlag, 1995.

22. Skogestad S and Postlethwaite I. *Multivariable feedback control analysis and design*. New York: John Wiley & Sons, 2001.

23. Franklin G, Powell J and Naeini A. *Feedback control of dynamic systems*. Boston, MA: Addison-Wesley Publishing, 2006.

24. Skogestad S. Simple analytic rules for model reduction and PID controller tuning. *J Process Control* 2003; 13: 291–309.

25. Lee Y, Park S, Lee M, et al. PID controller turning for desired closed-loop responses for SI/SO systems. *AIChe J* 1998; 44: 106–115.