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Smith predictor with sliding mode control for processes with large dead times

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The paper discusses the Smith Predictor scheme with Sliding Mode Controller (SP-SMC) for processes with large dead times. This technique gives improved load-disturbance rejection with optimum input control signal variations. A power rate reaching law is incorporated in the sporadic part of sliding mode control such that the overall performance recovers meaningfully. The proposed scheme obtains parameter values by satisfying a new performance index which is based on bi-objective constraint. In simulation study, the efficiency of the method is evaluated for robustness and transient performance over reported techniques.

Keywords: large dead time, Smith predictor, sliding mode, control input

1 Introduction

There is a challenge for any controller to deal with processes having large time delay. Generally, a controller gets any feedback from the process till it waits to pass the dead time. Dead-time is commonly observed in chemical, electronic, mechanical and biological systems. Several techniques have been reported to improve control of processes with time delay and summary of such methods on PI(D) tuning is given in [1]. It can be perceived from [1] that the number of tuning rules is much more for small time delay processes. In reality, large dead time processes cannot often be controlled well using a simple PI/PID controller. A PI/PID controller within the framework of a unity feedback control structure results in closed-loop step response with sluggish performance with large settling time for large time delay processes. Among all reported techniques, the Smith predictor (SP) is the most powerful control strategy because one can design the controller assuming the process is delay-free [2] and its variants [3–11]. Among these most recent methods on SP have been reported to stabilize the unstable and integrating processes with time delay. In [12], Smith predictor structure with a fuzzy fractional controller has been integrated within and its parameters were optimized by a genetic algorithm. The filtered Smith predictor with a measurable disturbance technique was proposed for open-loop unstable processes by Rodrguez *et al* [13].

Among many control techniques reported for processes with time delay, one noteworthy issue in the closed-loop control is parameter uncertainties. As such, demand continues to develop controllers which can work effectively in spite of uncertainties. Sliding Mode Controller (SMC) has evolved to deal with uncertainties and became well-known in control community once it was proposed by Utkin [14]. Basically SMC is a powerful strategy to design robust controller systematically even with uncertainty in systems [14–16]. A SMC in process control has been discussed more in [17, 18]. Their sliding technique was derived from a First Order Plus Dead time (FOPDT) model of the actual plant to control a type of nonlinear systems. The method later has been extended for open-loop unstable time delay processes in [19]. Later the authors in [20] presented simple predictive structure with sliding mode for three different controllers, namely an internal model based sliding mode controller, a time delay sliding mode controller, and a Smith predictor based sliding mode controller (SP-SMC). These control schemes showed the benefits for dealing with long time delays using the predictive structure plus the robustness of the sliding mode theory. However, their method for SP-SMC required six parameters to optimize in which two parameters for load disturbance rejection were found as per method given in [3]. Furthermore, the previous reported methods related to SP-SMC [17–19] had approximated the process deadtime using the first order Taylor series. Sivaramakrishnan *et al* [21] later presented this technique for extended delay-time constant ratio using an integral squared error (ISE) criteria. The results given in [21] have little improved the robustness to parameter uncertainties but not to disturbances. To overcome the delay approximation problem in those methods, again the Smith Predictor (or its variants) was adopted to eliminate deadtime together with SMC to achieve the robust controller [18]. This combination of SP and SMC was first time evaluated for integrating processes. The robustness to parameter variation and disturbance rejection was shown to be improved compared to the original structure of SP [18]. This structural technique was further improved for unstable processes [22] using power rate reaching law and the metaheuristic optimization algorithm.

In this work, we have proposed the enhanced control scheme for stable processes with large dead times using combination of SP and SMC. The presented technique in

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this paper requires less parameters to optimize compared to previously reported methods and without additional controller for load disturbance rejection. A new control performance index is also developed together with a discrete control law in SMC. The purpose of new control performance index is to give insight into the different criteria and their trade-offs between transient performance and actuator conservancy. Therefore, a metaheuristic search algorithm, namely Particle Swarm Optimization (PSO) is adopted to tune the control law optimally. The illustrative study is provided to verify the method and compare with related technique reported in the literature.

2 Smith Predictor with Sliding Mode

Since the performance of SP deceases in presence of modeling errors, Sliding Mode technique is combined togethe rwith SP to prove the robust procedure. The presented strategy combines the original SP structure while the main controller is a SMC. The configuration of the presented scheme is shown in Fig. 1 and the design of SMC goes as follows.

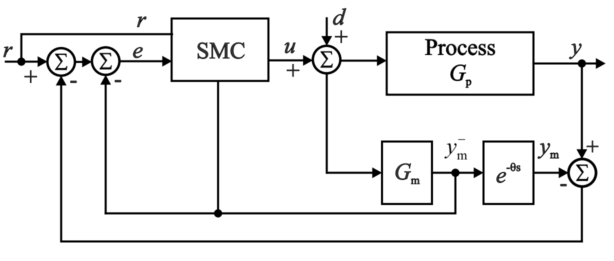

Fig. 1. Proposed Smith predictor with sliding mode structure

Basically SMC design follows two steps to implement that are first, the design of a stable surface and second, the design of a control law to force the system states onto the required surface in a finite time [16]. The designed surface is to match system uncertainties and disturbances. A reaching phase is defined when an initial phase of state trajectory is directed towards a sliding surface. However, the system can suffer from all types of disturbances. Therefore, a control rule can be planned which guarantees finite time reaching of sliding surface even in the presence of disturbances and mismatches. In this work, the sliding surface, $S(t)$, defined by [23] has been adopted to achieve the stability and tracking performance. The expression was defined with a characteristic of proportional, integral and differential types on the tracking error as

$$S(t) = \left(\frac{\mathrm{d}}{\mathrm{d}t} + \lambda\right)^n \int_0^t e(t)\mathrm{d}t \tag{1}$$

where n is the system order, e is the tracking error and λ is a tuning parameter to achieve the merit on the sliding surface. The control law is designed such that the state trajectory is forced for any initial condition towards the sliding surface and the trajectory remains on the surface thereafter [16]. It should be desired the state trajectory will hit the surface in fixed time using the control law. Once the state slides on surface and so the trajectory slides along the surface and hence the system is invariant to outer disturbances and parameter variations. The sliding equation (1) directs $S(t)$ to reach a constant value such that error is zero for all $t > 0$ and therefore

$$\frac{\mathrm{d}S(t)}{\mathrm{d}t} = 0\,. \tag{2}$$

After defining a suitable sliding surface, the control law is required to drive the controlled variable to its setpoint value. The sliding control law, $u(t)$ involves two parts, $u_c(t)$-continuous part and $u_d(t)$-discontinuous part. So it gives

$$u(t) = u_c(t) + u_d(t)\,. \tag{3}$$

The first part of $u(t)$ is obtained from the process states of input and output [14, 17]. In this work it is considered the continuous control part composed of the reference value, delay free model output and error value. So one can write u_c as

$$u_c(t) = f\big(r(t), y_m(t), e(t)\big). \tag{4}$$

Whereas the discontinuous part includes a nonlinear switching element like the ideal relay or saturation relay control. However, it is difficult to implement high-switching control practically using these ideal relay functions because of the presence of finite delay in the system or physical limitations of actuators. This causes a chattering problem around the steady state output [14, 17, 23]. Therefore a new type of function has been considered to reduce chattering phenomena without compromising on aggressiveness to grasp the sliding surface. In this scheme, we obtain the control law using power rate reaching law in which the switching function dynamics are specified a priori. This was analyzed firstly in [24] and given by

$$u_d(t) = \alpha|S(t)|^\beta \operatorname{sign}(S(t)) \tag{5}$$

where α and β are positive constants used to satisfy the condition in (2). A similar switching function, which delivered a potential advantage for unstable processes with dead times, was presented in [22] as well.

Since it is popular that the SP isolates the time delay, the process transfer function $G_p(s) = G_m(s)e^{-\theta s}$, is assumed with $G_m(s)$, a rational stable transfer function and θ, a time delay. A process model defined by stable first order transfer function without time delay as

$$G_m(s) = \frac{y_m^-(s)}{u(s)} = \frac{k_m}{\tau_m s + 1} \tag{6}$$

is used to design the SMC. Here, k_m and τ_m are gain and time constant, respectively. Then, (6) in differential form is written by

$$\tau_m \frac{\mathrm{d}y_m^-(t)}{\mathrm{d}x} + y_m^-(t) = k_m u(t)\,. \tag{7}$$

This gives

$$\frac{\mathrm{d}y_m^-(t)}{\mathrm{d}x} = \frac{1}{\tau_m}\big(k_m u(t) - y_m^-(t)\big). \tag{8}$$

Now the sliding surface can be developed for the first order process model and therefore by considering $n = 1$ in (1) one gets the proportional-integral expression as

$$S(t) = e(t) + \lambda \int_0^t e(t)\mathrm{d}t\,. \tag{9}$$

The above sliding surface must satisfy the condition in (2) and so it becomes

$$\frac{\mathrm{d}S(t)}{\mathrm{d}x} = \dot{e}(t) + \lambda e(t) = 0 \tag{10}$$

If regulatory problem is considered, the constant reference value can be discarded without any variation in performance. This results in the following simple expression

$$\frac{\mathrm{d}y_m^-(t)}{\mathrm{d}x} = \lambda e(t)\,. \tag{11}$$

Using (8) and (11), the continuous part of the control law is derived as

$$u_c(t) = \frac{1}{k_m}\big[\tau_m \lambda e(t) + y_m^-(t)\big]. \tag{12}$$

Finally, the complete form of the control signal from the SP-SMC can be generated as

$$u(t) = \frac{1}{k_m}\big[\tau_m \lambda e(t) + y_m^-(t)\big] + \alpha |S(t)|^{\beta}\operatorname{sign}(S(t)) \tag{13}$$

$$S(t) = \operatorname{sign}(k_m)\Big(\big(r(t) - y_m^-(t)\big) + \lambda \int_0^t e(t)\mathrm{d}t\Big). \tag{14}$$

The formation of above control signal (13-14) delivers a potential benefit from the process control point of view. First, $\operatorname{sign}(k_m)$ only relies on the static gain of the process; therefore the action never switches [17]. Second, the closed loop SMC has a fixed structure reliant on the λ and process model parameters. Further the controller equation (13) has three tuning parameters (λ, α, β). It is important to estimate the optimal values of parameters. In following section a new performance index, which can be satisfied using a suitable optimization algorithm for estimating proper tuning parameters, will be defined.

3 Optimal tuning of SP-SMC parameters

The controller design is a critical issue which demands many issues to be considered such has setpoint behavior, load disturbances, process perturbation, and measurement noise. These issues were presented for designing any classical PIDs in [25]. On the other hand, a low or no overshoot can introduce a long settling time and so the user has to choose between a fast response and a low overshoot. A new framework of bilevel optimization was proposed by Shi *et al* [26] to balance performance in terms of transient response, actuator preservation and robustness. In this case, the time weighted integral performance criteria particularly, the integral of squared-time-weighted-error (ISTE) criterion was employed in the design method. In addition to this, the constraint has been imposed using the control input variation and robustness indices. In regards to optimal disturbance rejection, Sun *et al* [27] had introduced a new constraint on relative delay margin. It discusses the issue encounters with the conventional robustness index like maximum sensitivity. Motivated by the analytical difficulties in dealing with robustness indices in process control, we introduce a new performance index giving insight into the bilevel optimization with a discrete control law in SMC and its trade-offs, not to give specific tuning method.

It has been shown in literature that if a controller is designed to minimize ISTE criterion then it typically guarantees satisfactory output, defined index as

$$J_{\mathrm{ISTE}}(x) = \int_0^{\infty} \big(te(x,t)\big)^2 \mathrm{d}t \tag{15}$$

where x indicates variable to be optimized. Because of the time weighting method in this formula, it penalizes the initial unavoidable errors which occur for setpoint changes. But, the optimal controller by this method may also not be sufficient to claim the best control input signal variations. A study reveals that abrupt difference in control signal is costly in terms of valve wearing and maintenance programs. If the total variation in the control input signal is measured to see how much efforts made to obtain the desired performance, then it can be measured simply by

$$\mathrm{TV} = \sum_{k=1}^{\infty} |u_{k+1} - u_k|\,. \tag{16}$$

Here, the index value TV should be as small as possible to say the variations in $u(t)$ is minimum to protect the actuator from wear and tear. In this work, our focus is not only to optimize the error signal criterion in (15), but also to minimize the risk of large control signal variation and to guarantee the robustness of the closed loop system against model inconsistency. Therefore, we define the combination of two performance criteria together to balance the tradeoffs between transient performance and actuator preservation as

$$\begin{gathered} J_{\mathrm{ISTE}} = \min_x \int_0^{\infty} \big(te(t)\big)^2 \mathrm{d}t \\ \text{subject to: } \mathrm{TV} = \min_x \sum_{k=1}^{\infty} |u_{k+1} - u_k|\,. \end{gathered} \tag{17}$$

Now keeping above performance requirement (17), we propose following objective function to find the optimal parameter values for (λ, α, β) as,

$$J_{\text{total}} = \sum_{k=1}^{t_f} (t_k e(k))^2 \mathrm{d}t + \frac{1}{\tau_m} \sum_{k=1}^{t_f} |u_{k+1} - u_k| \qquad (18)$$

where t_f is the total time of the experiment, and τ_m is the model time constant. In this objective function the constraint is imposed with respect to time constant of the process, meaning a less value of τ_m allowing some control signal variation. For example, a controller must be tuned to make small corrective actions if the process output changes fast with small control variation. Likewise the large control variation is necessary whenever the process output starts to drift from setpoint. After certain simulation study, the objective function (18) is formed to accomplish the foregoing behavior without compromising the performance. The trade-off for processes with large time delay is the design problem. The minimization of the objective function with only ISTE without robustness constraint gives controllers with poor robustness. The trade-off between transient performance and total input usage is controlled uniformly and optimally for diverse process dynamics by a single parameter, τ_m.

It is important to choose proper optimization technique to solve the objective function (18) without much convergence issue. There are various kinds of nature inspired optimization techniques, such as Genetic algorithm, Particle Swarm Optimization, Ant Colony, Cuckoo algorithm and many more survey in [28]. In the present work PSO algorithm produced good results and is adopted for the purpose of robust and global optimization. It has been shown that this algorithm results an optimum combination of parameter values and in a shorter time [29, 30]. In addition to this, the PSO has relatively less sensitive to the convergence and accuracy for small number of user defined parameters. The optimization constraint (18) can be satisfied using this global search technique for parameters (λ, α, β).

The basic PSO version with inertia weight is described in [30].

$$a_i \leftarrow \omega a_i + R(0, \varphi_1) \otimes (p_i - x_i) + R(0, \varphi_2) \otimes (p_g - x_i),$$
$$x_i \leftarrow x_i + a_i \qquad (19)$$

where $i \in N$, $\omega =$ inertia weight factor and $N =$number of particles (usually $N \leq 40$). The other parameters are as follows: x_i gives the particle present location and a_i defines the step velocity of the particle. The expression (19) has two parameters φ_1 and φ_2 determines the magnitude of the random forces in the direction of personal best p_i and neighborhood best p_g, mostly called acceleration coefficients. $R(0, \varphi_j)$, $j = 1, 2$; delivers a vector of random numbers uniformly distributed in $[0, \varphi_j]$. It is generated randomly after each iteration and for each particle.

The idea of above PSO algorithm is very simple, namely: at each case (iteration) when a given boundary is violated by any of the particles, the particle i is returned to its previous position x_i and the step a_i is reversed with the same magnitude, but in the opposite direction, *ie* $a_i = -a_i$. This simple heuristics has been tested on many simulated examples and it has been proven to work very stable. The following PSO parameters are utilized in the simulation after many trials in searching the best results by the proposed method.

- Initial setting of (λ, α, β) parameters is $(0.1, 0.1, 0.1)$, respectively.
- Population size$= 30$.
- ω is updated by

$$\omega = \omega_{\max} - (\text{it} - 1) \frac{\omega_{\max} - \omega_{\min}}{\text{it}_{\max} - 1} \qquad (20)$$

$$\begin{aligned} \omega_{\max} = 0.9\,, \quad \omega_{\min} = 0.1\,, \\ \text{it} = \text{current iteration}\,, \\ \text{it}_{\max} = \text{maximum iteration set} \end{aligned} \qquad (21)$$

- φ_1 and φ_2 are set to 0.2.

The algorithm has been developed in MATLAB 7.6 on Windows 7 core i5 Intel 4 GB RAM. The stopping criterion can be imposed by, either by using a fixed number of iteration or a given tolerance. Generally a fixed number of iteration is easy to implement and in this optimization the fixed iteration number is set to be 70, which is adequate for stated optimization task. The proposed technique of SP-SMC has proved the satisfactory results, as we can see from next numerical simulation.

4 Numerical simulations

In this section the closed-loop scheme Fig. 1 is analyzed with processes having large dead time. The study is given to compare the performance of the proposed scheme with some existing design approaches, when setpoint and disturbances changes are applied to the process. Finally, the performance is also examined under the parameter perturbation and measurement noise. The SMC parameters are tuned through the optimization fitness function corresponding to the minimization of J_{total} (18) using a PSO. The overall performance is assessed via overshoot (ov%), settling time (t_s) and ISTE as performance indices for comparison.

EXAMPLE 1. A second order process transfer function with large dead time $G_1(s) = e^{-10s}/(s+1)^2$, is considered. The FOPDT model was found to be given by $G_m(s) = e^{-10.87s}/(1.27s+1)$ [5]. Same process was studied by Kaya [5] and suggested PI controller from IMC-SP method is $(0.234 + 1/1.27s)$. Following the SP-SMC method discussed in Sections 2 and 3 the proposed controller parameters, (λ, α, β) are calculated as $(0.7109, 0.1, 2.4154)$. Responses to a unit step input change and disturbance with magnitude of -0.3 are given in Fig. 2. The controller performance is summarized in

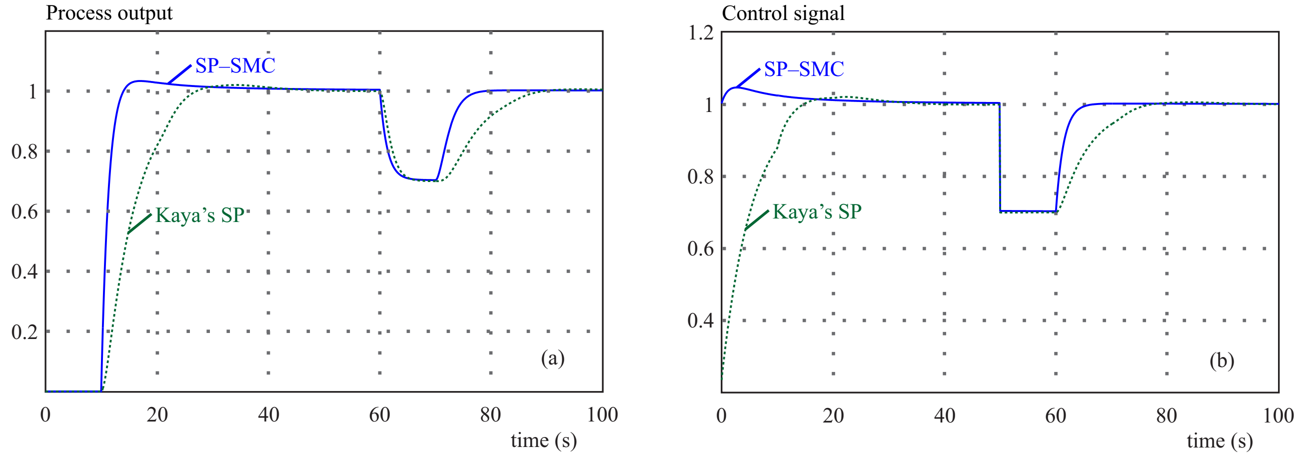

Fig. 2. Process outputs and inputs for Ex-1: blue line by the proposed method, red line by Kaya's [5] IMC-SP method

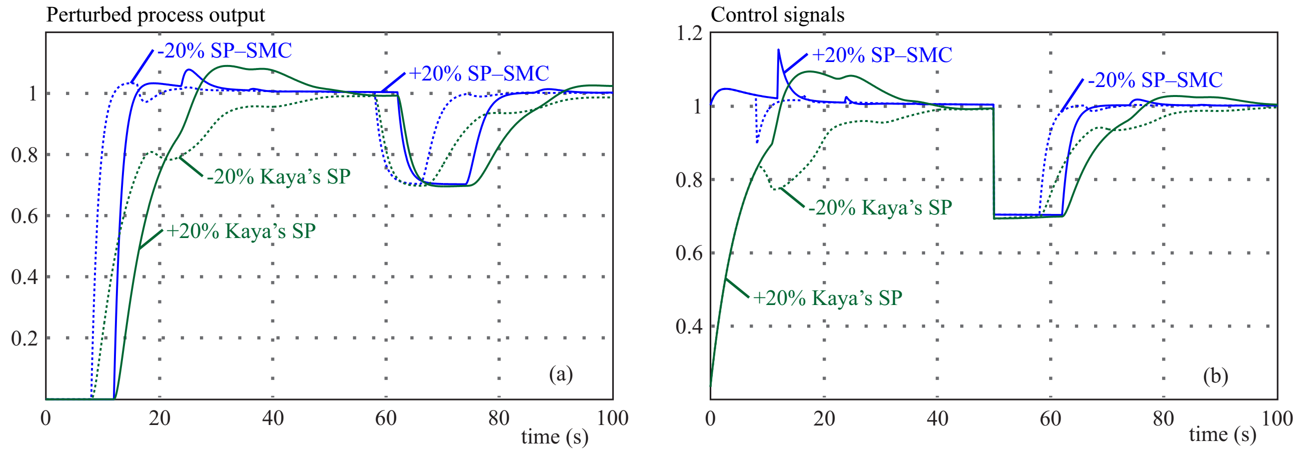

Fig. 3. Process outputs for $\pm 20\,\%$ change in dead time: blue line by the proposed method, red line by Kaya's [5]IMC-SP method

Table 1. It can be noticed that the presented approach results in least settling time and minimum ISTE value for the step response input. The step load disturbance is also rejected satisfactory. Additionally, the proposed method resulted in the desired performance in less control signal variations with TV=0.688 while in case with [5], the value was 1.421.

The robustness of the controlling method is necessary to check since the original SP is sensitive to modelling errors, especially to a mismatch in the dead time. By introducing an uncertainty of $\pm 20\,\%$ in the process dead time and for same controller parameters obtained before are used to observe the performance. Figure 3 shows again satisfactory robustness towards the assumed uncertainty in the process dead time.

EXAMPLE 2. This example considers a benchmark fourth-order process $G_2(s) = 1/(s+1)^4$, studied by Shi *et al* [26] and Sun *et al* [27]. Their FOPDT models to find parameters are given as $G_m(s) = e^{-2.075s}/(2.08s+1)$. Shi *et al*'s [27] bilevel optimization framework gave PID controller as $(0.8779 + 1/2.5548s + 0.5667s)$. For same $G_2(s)$, Sun *et al* [27] suggested PI controller with set-point prefilter using relative delay margin as a robustness index. Their method obtains the PI controller $0.54(1 + 1/2.08s)$ and set-point prefilter $\frac{1.248s+1}{2.08s+1}$.

For the proposed SP-SMC method, the controller parameters $\lambda = 0.7$, $\alpha = 0.7$ and $\beta = 3.0$ are obtained after satisfying the performance index (18). Static load disturbances of value -0.5 at $t = 50$s and -0.2 at $t = 80$s, respectively are assumed in the simulation. The responses of the closed-loop system for both controller settings are compared in Fig. 4. The controller performance is summarized in Table 1. It is obvious from the simulation results that SP-SMC controller provides a better set-point and load disturbance rejections than Shi and Sun's method. Under similar robustness, another advantage of SP-SMC is its smaller control input variation, corresponding to a less ISTE index value.

EXAMPLE 3. In this example a fourth order with large dead time process
$G_3(s) = e^{-10s}/[(s+1)(0.5s+1)(0.25s+1)(0.125s+1)]$ was used. For this process, a FOPDT model to estimate parameters is given as $G_m(s) = e^{-10.68s}/(1.3s+1)$ [20]. Camacho *et al* [20] proposed time delay sliding mode controller (TD-SMC) and obtained tuning parameters using time-domain performance index. Same process was study by the presented SP-SMC scheme in this paper.

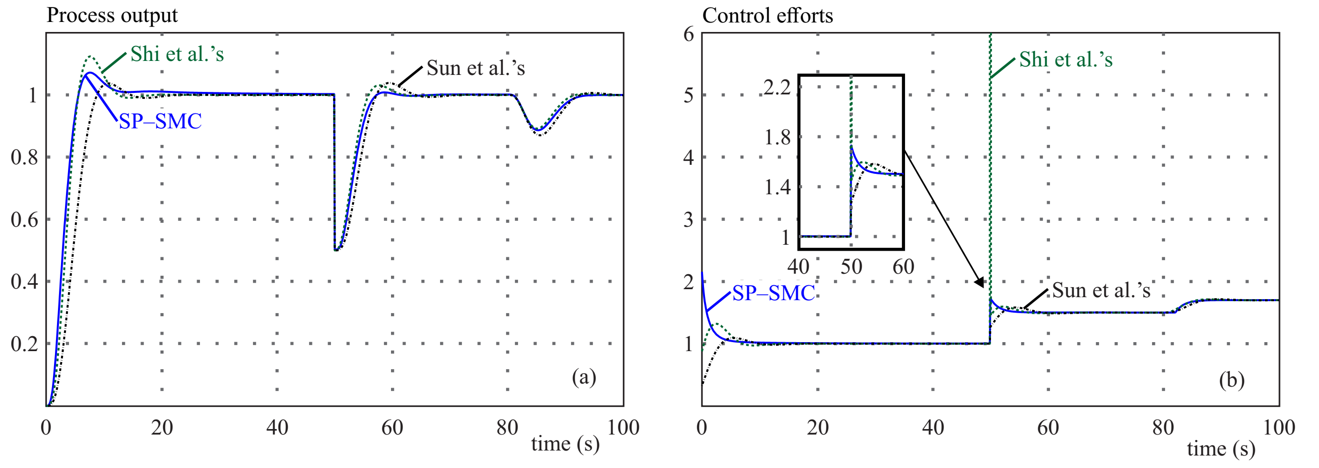

Fig. 4. Process outputs and inputs for Ex-2: blue line by the proposed method, red line by Shi *et al* [26] method, black line by Sun *et al*'s [27] method

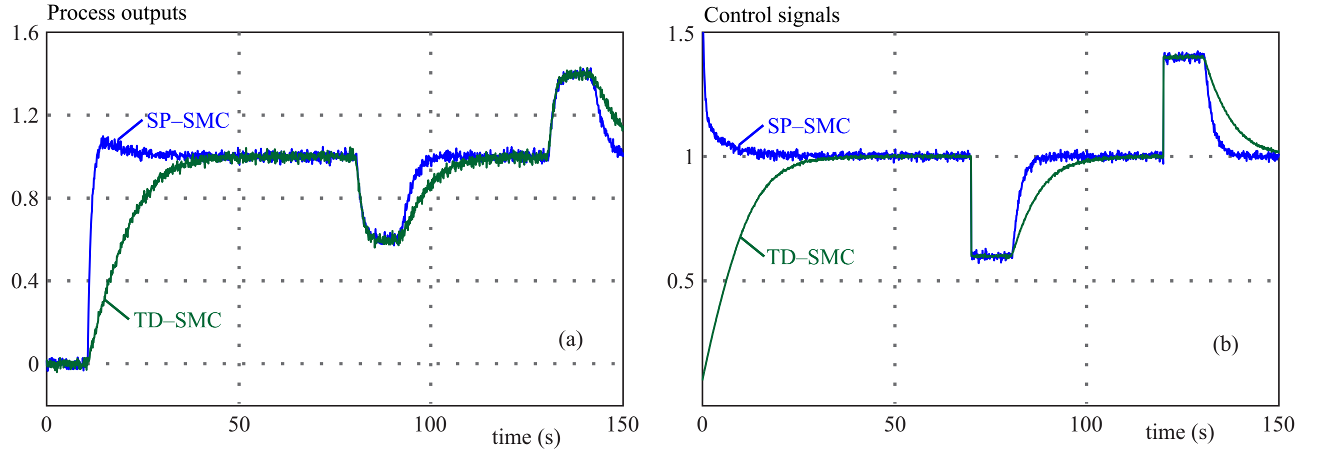

Fig. 5. Process outputs and inputs for Ex-3: blue line by the proposed method, red line by Camacho *et al* [20] method with 20 dB noise

Table 1. Performance assessment of the tuning methods

Process	Method	ov%	t_s (sec)	ISTE
G_1	Proposed	3.93	13.12	2.31
	[5]	0.0	27.13	20.29
G_2	Proposed	3.91	4.53	10.75
	[26]	12.37	10.36	39.24
	[27]	3.85	7.97	55.07
G_3	Proposed	7.51	16.29	7.79
	[20]	0.0	34.08	18.29

The performance index (18) gave the controller parameters $\lambda = 0.99$, $\alpha = 0.54$ and $\beta = 0.90$. To verify the usefulness of the SP-SMC scheme under realistic conditions, let the process output be corrupted by Gaussian distributed random noise with SNR value 20 dB. Also, the process with both controllers, SP-SMC and TD-SMC [20], was evaluated against setpoint changes and load disturbances. The process output and input responses are depicted in Fig. 5. Table 1 gives the performance comparison. It is observed that the SP-SMC method gives a significant improvement in tracking and disturbance rejection, compared with the existing method. It was noted that the control output variations, TV was measured 6.923 whereas the controller TD-SMC gave 6.274. There is a little bit more control signal variation measured in the proposed method. However, the proposed methods responded faster to the step input and load disturbance changes. In this way, the controller scheme presented in this work gives the balanced trade-offs between transient performance and actuator preservation and to guarantee the robustness of the system.

5 Conclusions

The paper presented a Smith predictor with sliding mode controller for long dead time processes. This control scheme showed the merits for dealing with long dead time using the Smith predictor plus the robustness of power rate sliding law. A new performance index is formulated to satisfy both proper transient responses and smooth control actions, hence can preserve actuators from untimely attrition. The scheme worked well for both the transient performance and robust disturbance rejection and even when process perturbations and measurement noise were considered. Examples demonstrate that the SP-SMC scheme gives better performance than the some previous approaches. A disadvantage of this scheme is the large computational time to obtain optimal parameter values for underline control law.

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