# An Optimization of Robust Modified Smith Predictor Control Strategy for Integrating Processes with Dead-time

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## ABSTRACT

The presence of an integrator and dead time in physical processes reduces stability and robustness. It limits the response time of a system. Integrating plus dead time (IPDT) processes provide oscillatory and slow response if the parameters of a system are not tuned properly despite dead time compensators (DTCs) being used. To overcome these shortcomings, the Smith predictor-based sliding-mode control (SP-SMC) strategy using the Jaya optimization technique for IPDT processes is proposed in this study. For the selected populations, the cost function and best controller parameters are evaluated.

The proposed strategy is compared with the typical Smith predictor-based proportional, integral and derivative (SP-PID), and conventional SP-SMC design methods. To evaluate the performance, integrating first-order with dead time (IFODT) process models with different controllability relationships (CR) is considered. Robustness analysis of the controller is carried out in this study for 30% parametric uncertainties and bounded disturbances.

The simulation tests on a laboratory process (level) control system reveal the supremacy of the Jaya optimization algorithm over prevalent control strategies. Compared to SP-PID and SP-SMC, the proposed design method shows an improvement of 33.07% and 12.58% in settling time and an improvement of 19.73% and 22.93% in rise time with 0% overshoot, respectively. The applied setup elicits better multi-level set point tracking and disturbance rejection capabilities with the step input. Besides, the proposed algorithm shows better closed-loop performance for numerical simulations of Models 1 and 2.


**Keywords**: Dead time, Integrating processes, Jaya optimization algorithm, PID control, Smith predictor, Sliding mode control

Manuscript received on June 4, 2022; revised on July 23, 2022; accepted on October 4, 2022. This paper was recommended by Associate Editor Matheepot Phattanasak.

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Digital Object Identifier: 10.37936/ecti-eec.2023212.249821

## 1. INTRODUCTION

Without dead time, the transient behavior of a process is said to be normal. Proportional, integral derivative (PID) controllers are widely used in both stable and unstable industrial processes. Integrating plus dead time (IPDT) processes are typical of unstable systems. However, due to the structural limitations of the PID controller, with step input, the control performance is slow and oscillatory. Researchers have used a modified PID (PI-PD) structure for controlling unstable processes with delay time [1].

Most chemical processes exhibit unstable and inverse responses due to changes in the input variable, while open-loop unstable processes do not reach steady-state conditions. Fine-tuning of the control law is required to enhance performance. However, for a better controllability relationship (CR), the control of the process becomes difficult [2–3].

An optimal PI-PD controller has been explored for IPDT processes under the consideration of difficult dynamics where the control variable continuously increases or decreases in accordance with changes in the manipulated variable [4] while a predictive PID control strategy was implemented for second-order plants with dead time elements by considering difficult dynamics or a more complex system [5].

Various authors have implemented hybrid model-based control strategies for complex industrial systems such as heat exchangers [6], artificial intelligence-based composition and level control in a distillation column [7], liquid storage tank [8], neural network-based continuous stirred tank reactor control [9], etc. for controlling IPDT processes. Ibrahim Kaya provided optimum tuning rules for integral-proportional derivative (IP-D) controller parameters. The superiority of the proposed method was validated using simulation tests [10].

Anil and Sree used the direct synthesis (DS) approach to design a pure integrating process to boost the performance or robustness of the system [11] while Moina Ajmeri and Ahmmed Ali presented a modified Smith predictor (SP) for pure integrating, integrating plus first-order, and double integrating processes with large time delays. For tuning the controller parameters, the DS approach was used. The usefulness of the proposed strategy was validated via simulation tests [12]. Kumar and Sree reported internal model control-based PID designs for first and second-order integrating processes with dead time by approximating higher order into lower order processes without considering the inverse system dynamics [13]. Begum et al. investigated performance using the same strategy for non-minimum phase processes by applying the H2 minimization criterion [14]. However, the stability issue remains unsolved.

Matausek and Ribic designed a modified SP as a PID controller in series with a second-order filter for stable, integrated, and unstable processes including time delay. They conducted simulation and experimental tests on a laboratory thermal process set up to elicit improved performance with constrained optimization [15]. Torrico et al. presented new tuning rules using DTCs for stable, integrated, and dead-time processes. They provided self-tuning guidelines for a DTC filter to improve robustness and measurement noise attenuation in the thermal chamber. However, for the prediction of error, the authors used an extra loop, making the control structure complicated [16]. To overcome these difficulties, generalized SP was used by Sanz et al., utilizing the proposed filter to predict non-delayed output [17].

Among the control techniques suggested for IPDT processes, the noteworthy issues with the PID controller and its variants are stability, robustness, parametric uncertainties, and disturbance suppression capabilities. Hence, sliding-mode control (SMC) as a robust controller and hybrid control strategies have evolved to deal with the above issues.

Ozbek elaborated on the genetic algorithm-based first-order SMC structure for a time-delay system. He optimized the controller parameters for performance evaluation in terms of transient response, tracking problem, and disturbance rejection capability [18]. These authors presented hybrid control topology for a modified SP-based SMC (SP-SMC) to improve the regulatory performance of an unstable system by formulating a new control law. The simulation study validates the proposed control strategy [19] while Mehta and Kaya explored the SP-SMC structure for elevated dead time processes to improve the load-disturbance performance with less variation in the input control signals. A new performance index has been formulated and tested against perturbations in system parameters. However, with the proposed control design, more computational time is required to obtain the optimal parameters [20].

Espin et al. proposed a dynamic SMC and SP method for the IPDT process (coupled tank system) with a long dead time. They approximated a higher-order model of the coupled tank to a first-order IPDT model. The proposed topology gives improved performance, reduced chattering, and improved robustness [21]. Princes et al. explored a modified SP- SMC technique for dead time processes, modifying the tuning equations to enhance the robustness of the system. The model-based tuning rules are verified via the simulation studies. Non-overshoot introduces a large settling time [22]. Musmade and Patre synthesized an SMC by identifying a second-order plus dead time model and state predictor. Stability was ensured via reachability conditions. The proposed design method was validated using the simulation results and provided better performance compared to prevalent strategies [23].

Ozbek addressed the optimal values of controller parameters using a genetic algorithm. The control performance of the SP-SMC structure was verified for tracking, transient response, and bounded disturbance rejection [24]. Kumar et al. reported a "whale optimization" variable structure control technique for unstable processes. The reported method provided superior performance for an inverted pendulum system in the presence of disturbance and noise [25].

Kumar and Ajmeri used a "whale optimization" algorithm to find the optimal values of a variable structure control system for improving the robustness of an unstable system. The proposed strategy has been applied to non-minimum phase and non-linear systems in the presence of external disturbances and noise [26]. The authors applied a grasshopper optimization algorithm to an unstable second-order plus a dead time-based-SMC model, claiming minimum values of error performance indices with respect to matched uncertainty and measured noise [27].

Tiacharoen and Chatchanayuenyong designed PID, SMC, and fuzzy logic-based SMC for a dynamic voltage restorer system. To find the optimal parameters, they used a bee algorithm for the compensation of load voltage. Simulation and experimentation were used to validate the proposed strategy [28]. However, although the researchers have used optimization algorithms to find the optimal values of decision variables, more algorithm-specific and control-specific parameters and more computing time are required in the optimization process.

Table 1 presents a summary of the research gaps identified from the literature survey. One of the articles considered the control schemes for IPDT processes using a combination of modified SP and SMC with different CR. To find the optimal parameters, a new parameterless Jaya optimization algorithm has been used.

Significant contributions:

1. For the first time, a hybrid control topology (SP and SMC) with parameterless optimization algorithm (Jaya) is used for an IPDT plant.
2. Different CRs are considered for synthesizing controller performance.
3. Modified SP-based controllers and optimization-based control designs are compared. The quantitative performance of time-domain specifications and error-based performance indices are evaluated.

Impact of the contributions:

1. Optimal parameters are obtained according to the search dimension, resulting in the improved performance of closed-loop IPDT plants.
2. Better quantitative performance in terms of time-domain specifications such as settling time, rise time,

***Table 1**: Summary of identified research gaps.*

| Authors | Research Gap |
|---|---|
| [1-5] | Limitations of PID, Steady-state error, Stability reduction and Worst performance for elevated dead-time. |
| [6-10] | Robustness problem due to dead-time, Oscillatory and slow response, Disturbance suppression capabilities and Imprecise tuning. |
| [11-18] | Stability performance degradation due to uncertainties and imprecise tuning. |
| [19-27] | Parameter tuning, No specific tuning rules and More adjustable parameters. |

percentage overshoot, integral absolute error (IAE), and integral square error (ISE).

The paper is structured as follows: The next section formulates the problem, motivation, and system description. Section 3 covers the preliminaries, while section 4 describes the proposed methodology. The results and discussion are covered in section 5 while section 6 investigates the performance of the proposed strategy using Models 1 and 2 as case studies. Lastly, the concluding remarks are conferred.

## 2. PROBLEM STATEMENT, MOTIVATION AND SYSTEM DESCRIPTION

### 2.1 Problem Statement

Many industrial IPDT systems are approximated by the following form [13]

$$G_p(s) = \frac{k_p e^{-ds}}{s(\tau s + 1)} \tag{1}$$

In Eq. (1), $k_p$: Steady state gain, $\tau$ : Time constant, $d$: Dead time of the process, $\frac{k_p}{s}$ is the rational part, $kp > 0$ and dead-time $d$.

In reality, IPDT processes are difficult to control by conventional methods. A classical SP with an IPDT plant results in steady-state error under constant load disturbance due to the inclusion of "integral" action. Hence, a modified SP is used to overcome these shortcomings. In addition, dead time reduces stability and limits the response time of a system. A robustness problem exists due to the dead time although DTC is used.

Many researchers have used PID control and the SP-structure to tackle these problems. However, reference-point change and disturbance suppression responses are slow and oscillatory. A large number of adjustable parameters are involved in controller synthesis. Again, there are no effective tuning rules available.

### 2.2 Motivation

To handle parametric uncertainties and bounded disturbances, an SMC is used in this study. However, "chattering" is the main issue with a conventional SMC. Robustness is improved slightly, although the disturbance suppression issue remains unsolved. Imprecise tuning of the sliding surface and total control law parameters lead to poor performance, and SP as a DTC has a robustness problem associated with dead time. Hence, the main motivation behind this study is to achieve robustness, stability despite uncertainties, external disturbances, precise tuning of system parameters, and an acceptable performance.

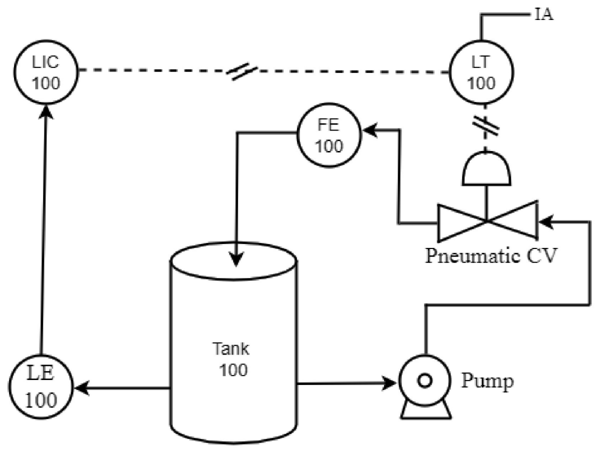


***Fig. 1**: P&ID of laboratory level control.*

### 2.3 System Description

The process and instrument diagram (P&ID) of the laboratory level control system is depicted in Fig. 1. It consists of a submersible pump and a level transmitter LT (type-electronics, two wire transmitters, range: 0–250 mm and output 4–20 mA DC) to sense the level; fitted on transparent process tank with a graduated scale ranging from 0–100%. The pneumatic control valve (size: ¼-inch, input: instrument air (IA)- 3-15 psig, air to close type) through a current-to-pressure converter, adjusting the inlet flow rate of water into the tank. The controller LIC is interfaced with the computer via a USB port for inspecting the process through supervisory control and data acquisition (SCADA) mode.

## 3. PRELIMINARIES

This section introduces the basic concepts of SMC and modified SP (used as a DTC).

### 3.1 Sliding Mode Control

Basically, the SMC design includes a stable sliding manifold $s(t)$ and the formulation of total control law $u_{total}$. The process dynamics are restricted on the sliding manifold. The sliding surface matches the system uncertainties and bounded disturbances. A control law is designed to direct the system trajectories to the sliding surface. The convergence of the sliding surface to zero depends on tracking error, order of the system, and associated gain coefficient. It is represented as [29]

$$s(t) = f[n, \lambda, e(t), \int e(t)dt, \dot{e}(t), ] \quad (2)$$

In Eq. (2), $e(t)$ is the error signal, $\lambda$ represents the sliding surface $s(t)$, and $n$ devises the order of an uncontrolled structure. The aim is to force the system state (error) to the sliding surface. Once the reference point is reached, the sliding surface acknowledges a constant value if, and only if, $\dot{s}(t) = 0$.

$$u_{total}(t) = u_c(t) + u_d(t) \quad (3)$$

where, an equivalent control input $u_c(t)$ is formulated from the input and output states. Switching the control input $u_d(t)$ incorporates the switching element, given as [31]

$$u_d(t) = k_d sgn(s(t)) \quad (4)$$

The "sgn" term in Eq. (4) is responsible for chattering. To reduce the chattering, a "sigmoid" function can be used as indicated by Eq. (5) where kd is the switching gain and $\delta$ is the boundary layer thickness. Both parameters are bounded for chattering [30]

$$u_d(t) = k_d \frac{s(t)}{|s(t)| + \delta} \quad (5)$$

### 3.2 Smith Predictor

The modified SP is used as the DTC whose architecture is represented in [20]. The stable rational process transfer function with dead time is presented as

$$G_p(s) = G(s)e^{-ds} \quad (6)$$

Without the dead time element, the transfer function process is $G_m(s)$ which is used to predict the effect of the control action on output response. $G_m(s)$ is constructed as [19]

$$G_m(s) = \frac{X_1(s)}{u(s)} = \frac{k_m}{(\tau_m s + 1)} \quad (7)$$

Eq. (7) is used to design the SMC, based on the delay free part of process transfer function. $k_m$ and $\tau_m$ are the static gain, and time constant respectively. $X_1(s)$ is the model output without the dead-time element. $u(s)$ is the controller output applied to the process model. In differential form, it can be written as

$$\dot{X}_1(t) = \frac{1}{\tau_m}\left[k_m u(t) - X_1(t)\right] \quad (8)$$

The original SP structure cannot reject constant load disturbances. A proportional derivative controller $p_d(s)$ is adopted for load disturbance rejection whose transfer function is given by [19] (Fig. 3)

$$p_d(s) = k_0(\tau_d s + 1) \quad (9)$$

where, $k_0 = 0.7239/k_m(\tau_m + \tau_d)$ and $\tau_d = 0.4(\tau_m + \tau_d)$.

## 4. METHODOLOGY

This section introduces a modern optimization algorithm (Jaya) which is used to find the optimal values for the decision variables of the SP-based SMC and governing equations.

### 4.1 Jaya Optimization Algorithm

To solve many constrained and unconstrained optimization problems, a new, parameterless Jaya optimization algorithm was introduced in 2015 by Rao [32–33]. In the searching process, the Jaya optimization algorithm avoids the "worst" solutions and selects the "best." It updates the best solution again, i.e., in short, it is the optimization algorithm with the best-worst play searching mechanism. The Jaya algorithm consists of population size and number of iterations as the termination criteria. It does not require scaling and cross-over parameters.

Consider $g(x)$ with D-dimensional factors ($m = 1, 2, ..., N$) and $j_{l,m}$ as estimated value of $m^{th}$ variable at solution. The position of $l^{th}$ solution is $j_l = (j_{l,1}, j_{l,2}, ...j_{l,N})$ while the best solution is $j_{best} = (j_{best,1}, j_{best,2}, ...j_{best,N})$. The worst solution is $j_{worst}(j_{worst,1}, j_{worst,2}, ...j_{worst,N})$. $j_{best}$ indicates the best estimation of the function $g(x)$.

The best-worst play procedure of Jaya optimization algorithm is given as in [34]

$$j_{l,m}^{new} = j_{l,m} + r_1\left[j_{best} - \left|j_{l,m}\right|\right] - r_2\left[j_{worst} - \left|j_{l,m}\right|\right] \quad (10)$$

In Eq. (10), $j_{l,m}^{new}$ is the updated solution of $j_{l,m}$. $j_{best}$ and $j_{worst}$ are the best and worst solution of $m^{th}$ variable. $\left|j_{l,m}\right|$ is the absolute value of $j_{l,m}$. The weights $r_1$ and $r_2$ are arbitrary numbers within [0,1]. ($j_{best} - \left|j_{l,m}\right|$) indicates that the search process moves towards for finding the best solutions while ($j_{worst} - \left|j_{l,m}\right|$) explores the worst solutions which later gets discarded. The update of solution takes place if the condition $j_{l,m}^{new} > j_{l,m}$ gets satisfy.

Fig. 2 shows schema of Jaya optimization algorithm that mainly includes an initilisation process, best-worst play process, updation of the best solution, rejection of worst solution till termination criterion met. The best solutions are considered as optimal solutions.

Fig. 3 explores the proposed SP-SMC tuning strategy in which optimal values of decision variables are obtained from Jaya optimization algorithm are used as controller parameters for evaluating the performance of IPDT process represented by Eq. (1).

### 4.2 Governing Equations in Controller Design

Referring to Eq. (7) and Fig. 3, the transfer function of the IPDT model without plant or model mismatch is [17].

$$G_m(s) = \frac{X_1(s)}{u(s)} = \frac{k_m}{s(\tau_m s + 1)} \quad (11)$$

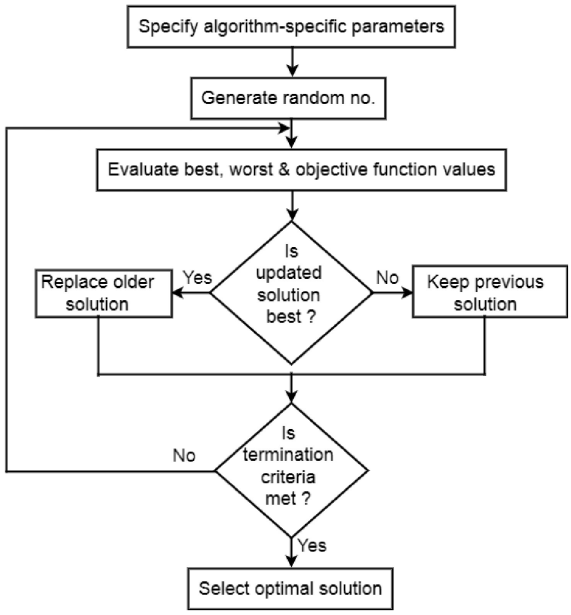


***Fig. 2***: *Schema of Jaya optimization.*

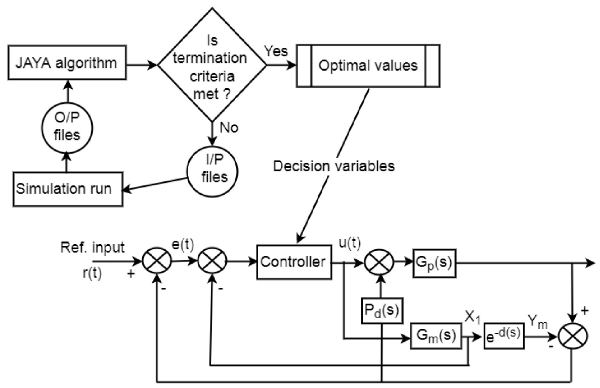


***Fig. 3***: *The proposed SP-SMC tuning.*

where, $u(s)$ indicates controller output. In differential form, Eq. (11) can be rewritten as

$$\ddot{X}_1(t) = \frac{1}{\tau_m}\left[k_m u(t)\right] - \dot{X}_1(t) \tag{12}$$

The PID sliding surface $s(t)$ is selected as [30]

$$s(t) = \lambda_1 e(t) + \lambda_0 \int_0^t e(t)dt + \dot{e}(t) + \tag{13}$$

with $\dot{s}(t) = 0$, Eq. (13) yields [29],

$$\ddot{s}(t) = \ddot{e}(t) + \lambda_1 \dot{e}(t) + \lambda_0 e(t) = 0 \tag{14}$$

However, $e(t) = r(t) - X_1(t)$ where, $r(t)$ is the command signal and $X_1(t)$ is output of the delay free part as indicated in Fig. 3. Substituting the expression $e(t) = r(t) - X_1(t)$ in Eq. (14), yielding,

$$\ddot{r}(t) - \ddot{X}_1(t) + \lambda_1 \dot{r}(t) - \lambda_1 \dot{X}_1(t) + \lambda_0 e(t) = 0 \tag{15}$$

***Table 2***: *Control-specific parameters of the Jaya optmization algorithm.*

| Parameters | Value |
|---|---|
| RUNS | 15 |
| Size of population | 40 |
| Iterations (maximum) | 100 |
| Decision variables | 4 |
| Total function evaluations | 10000 |
| Termination condition | Iterations (maximum) |

As the derivative of the reference-point step input signal does not have any effect on control performance, it can be neglected [30]. Therefore, Eq. (15) can be reworked as

$$\ddot{X}_1(t) = -\lambda_1 \dot{X}_1(t) + \lambda_0 e(t) \tag{16}$$

Put Eq. (12) into Eq. (16), one has an equivalent control input $u_c(t)$ as

$$u_c(t) = \frac{1}{k_m}\left[(1 - \tau_m \lambda_1)\dot{X}_1(t) + \tau_m \lambda_0 e(t)\right] \tag{17}$$

From Eqs. (5) and (17), the complete SP-SMC control law is,

$$u_{total}(t) = \frac{1}{k_m}\left[(1 - \tau_m \lambda_1)\dot{X}_1(t) + \tau_m \lambda_0 e(t)\right] + k_d \frac{s(t)}{|s(t)| + \delta} \tag{18}$$

The sliding surface expression is [20],

$$s(t) = sign(k_m)\left[-\dot{X}_1(t) + \lambda_1 e(t) + \lambda_0 \int_0^t e(t)dt\right] \tag{19}$$

Eqs. (18) and (19) are the governing equations used for controller implementation. Based on the CR, the gain coefficients of the sliding surface and total control input are calculated from the tuning equations presented by Mehta and Kaya [20].

## 5. RESULT AND DISCUSSIONS

To illustrate the closed loop performance of proposed method, laboratory level system as depicted in Fig. 1 is modelled as IFODT process. Transfer function is obtained using 'system identification' toolbox of MATLAB R2014a. The transfer function is,

$$G_p(s) = \frac{e^{-4.8s}}{s(3.95s + 1)} \tag{20}$$

Eq. (20) indicates IPDT process whose time-constant is 4 seconds, dead-time is 6 seconds, static gain is 1 and CR is 1.22.

### 5.1 Optimal Tuning of SP-SMC

In this study, the control-specific parameters of the Jaya optimization algorithm are presented in Table 2. The bounds of the decision variables ($\tau_0, \tau_1, k_d$, and $\delta$ of Eq. (18)) are selected as $lb = [0, 0, 0, 0]$ and $ub =$

***Table 3**: Optimal values of decision variables for the SP-SMC via Jaya optimization algorithm, BV: Best value and WV: Worst value.*

| Trial No. | $\lambda_0$ | $\lambda_1$ | $k_d$ | $\delta$ | $J_1$ | $J_2$ |
|---|---|---|---|---|---|---|
| 1 | 0.101 | 0.36 | 4.50 | 0.78 | 6.325 | 4.0312 |
| 2 | 0.130 | 0.51 | 3.20 | 0.56 | 9.18 | 4.012 |
| 3 | 0.001 | 0.30 | 3.80 | 0.50 | 4.926 | 3.823 |
| 4 | 0.006 | 0.60 | 5.11 | 0.42 | 5.23 | 4.204 |
| 5 | 0.002 | 0.24 | 3.92 | 0.31 | 6.185 | 4.016 |
| BV | 0.001 | 0.30 | 3.80 | 0.50 | 4.926 | 4.0104 |
| WV | 0.101 | 0.36 | 4.50 | 0.78 | 6.325 | 4.912 |

***Table 4**: Convergence point of cost functions (Eq. (23)).*

| Strategy | Convergence ($C_{f1}$) | Convergence ($C_{f2}$) |
|---|---|---|
| SP-PID | 20 | 09 |
| SP-SMC | 11 | 07 |
| SP-SMC Tuned | 08 | 07 |

[0.1, 0.5, 5, 1]. *"lb"* represents the lower bound while *"ub"* indicates the upper bound of the decision variables. Table 3 presents the optimal values of the controller parameters, objective function values, and the best and worst solutions. Out of 15 trials, the results of the best 5 trials are presented. Two objective functions are selected as shown below.

$$J_1 = IAE = \int_0^t |e(t)|\, dt \tag{21}$$

$$J_2 = ISE = \int_0^t |e^2(t)|\, dt \tag{22}$$

Eqs. (21) and (22) are practiced to improve the dynamic response of the system for small and large errors, respectively. According to Table 3, Trial 3 confers the minimum objective function values. Therefore, the selected values are $\tau_0 = 0.001$, $\tau_1 = 0.3$, $k_d = 3.8$, and $\delta = 0.5$. These values are used in the simulation tests to illustrate the performance of the IFODT process.

Consider a cost function $C_f$ as [34]

$$C_{fi} = \frac{1}{1 + J_i} \tag{23}$$

where $i = 1, 2$ and $J_i$ is the objective function represented by Eqs. (21) and (22). Table 4 indicates the convergence point of the cost functions depicted in Fig. 4. Fewer iterations are required for SP-SMC tuned method via the Jaya optimization algorithm to converge the cost functions.

## 5.2 Nominal System Response

In the design of a typical SP-PID, three terms $k_p$, $k_i$, and $k_d$ for the PID controller are obtained with the "PID Tuner." It automatically tunes the gains of a PID controller. The parameters are found as $k_p = 0.50976$, $k_i = 0.00196$, and $k_d = 1.4078$ with a filter coefficient of $N = 0.7660$.

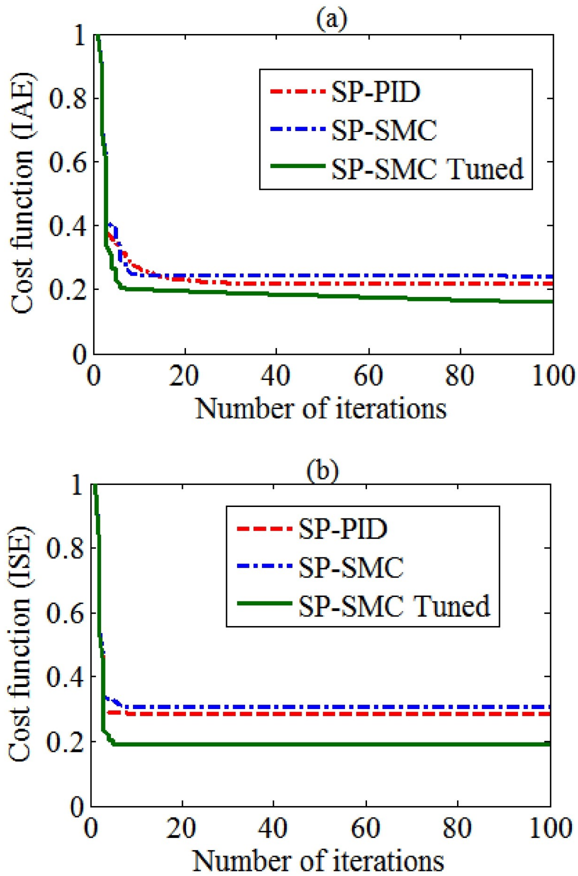


***Fig. 4**: Convergence test for cost functions J1 and J2. (a): IAE, (b): ISE.*

For a classical SP-SMC structure, the parameters are calculated from the tuning equations formulated by Camacho and Rojas [35]. The parameters are found to be $\lambda_0 = 0.25$, $\lambda_1 = 4$, $k_d = 0.551$, and $\delta = 1.492264$ while $p_d(s) = 0.292s + 0.073$.

For the proposed control method, parameters ($\lambda_0 = 0.001$, $\lambda_1 = 0.3$, $k_d = 3.8$, $\delta = 0.5$, and $p_d(s) = 0.292s + 0.073$) are evaluated from Table 3 (best values) and used for the simulation tests. The proportional-derivative (PD) controller for load disturbance remains the same for the SP-SMC method and recommended strategy.

Fig. 5 (a) illustrates the closed-loop response for applied control input. The proposed control algorithm shows a non-overshoot response while 5.97% and 11.51% overshoots can be observed for SP-SMC and SP-PID designs, respectively. The corresponding controller output $u(t)$ is depicted in Fig. 5 (b) which devises the smooth control signal for the suggested technique. The learning curves of the sliding surface in Fig. 5 (c) reveal that the sliding surface unites to zero at 9.861 seconds and 79.63 seconds with the proposed technique and SP-SMC strategy. It can be concluded from Fig. 5 (a–c) that the Jaya optimization algorithm shows better performance than other control design methods.

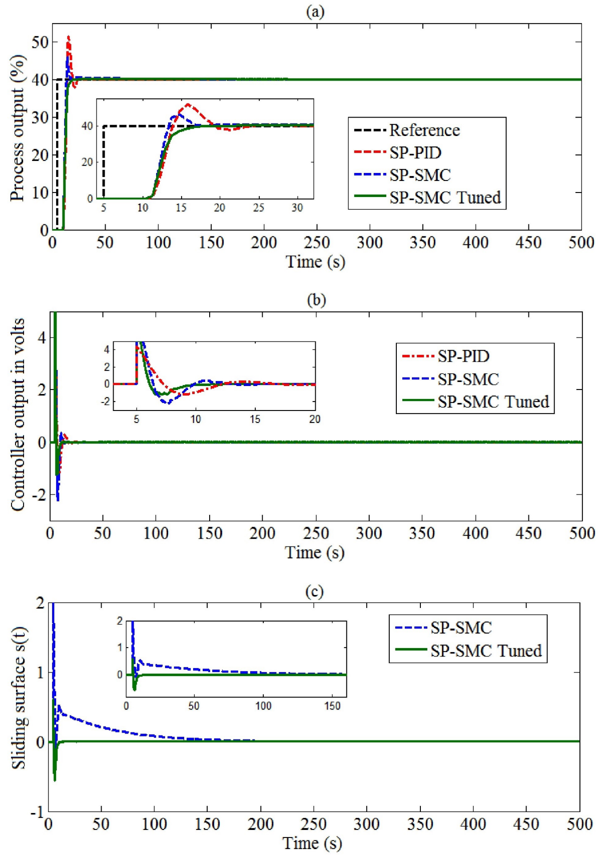


***Fig. 5**: Nominal process response. (a): Output response $y(t)$, (b) Controller output $u(t)$, and (c): Sliding surface $s(t)$.*

Table 5 presents a quantitative summary of the time-domain specifications and performance indices evaluated in Fig. 5 (a). The proposed technique shows a zero percentage overshoot. The SP-SMC tuning via the Jaya algorithm shows superior performance compared to other methods as can be observed from Table 5. Table 6 shows the percentage improvement in time-domain specifications and error-based performance indices of the proposed strategy over classical methods.

### 5.3 Reference Point Change and Disturbance Rejection Response

This subsection explores the reference change performance and bounded disturbance rejection to apply the step signal as an input. The reference-point changes from 40 to 60% at $t = 200$ (sec.) and from 60 to 40% at time $t = 300$ (sec.). A pulse disturbance of $\pm 6\%$ is applied at $t = 125$ (sec.), and at $t = 400$ (sec.) for the duration of 10 (sec.) in each response. Fig. 6 (a) and Fig. 6 (b) manifested output response and associated control efforts, respectively. The proposed method exhibits superior performance compared to prevalent techniques.

***Table 5**: Summary of time-domain specifications and performance indices.*

| Controller Type | $T_s(sec.)$ | $T_r(sec.)$ | $M_p(\%)$ | $J_1$ | $J_2$ |
|---|---|---|---|---|---|
| SP-PID | 25.31 | 2.89 | 11.51 | 6.701 | 5.789 |
| SP-SMC | 19.31 | 3.01 | 5.89 | 5.057 | 4.003 |
| SP-SMC Tuned | 16.88 | 2.32 | 0.00 | 4.796 | 3.765 |

***Table 6**: Percentage improvement using the proposed strategy.*

| Control Method | in $T_s(\%)$ | in $T_r(\%)$ | in $J_1(\%)$ | in $J_2(\%)$ |
|---|---|---|---|---|
| SP-PID | 33.07 | 19.72 | 28.43 | 34.96 |
| SP-SMC | 12.58 | 22.92 | 5.16 | 5.95 |

### 5.4 Robustness Analysis

The nominal control performance in the presence of 30% parameter uncertainty with the associated control signal is depicted in Fig. 7 (a–b) respectively. To analyze the robustness of the controller, a 30% reduction is considered in the dead-time element and time constant of the model, and a 30% increase in the static gain of the process.

Considering 30% parameter uncertainty, the transfer function of IFODT process becomes,

$$G_p(s) = \frac{1.3e^{-4.2s}}{2.8s^2 + s} \tag{24}$$

As can be observed from Fig. 7 (a), the SP-SMC and SP-PID strategies exhibit a 2.56% and 11.78% overshoot in the process output respectively, whereas the proposed control technique shows a non-overshoot response. Fig. 7 (b) indicates a reasonably smooth control effort.

## 6. CASE STUDIES

In this section, a second-order integrating process $G_1(s)$ with $CR = 0.1168$ and process $G_2(s)$ with $CR = 4$ are considered to evaluate the performance of the reported control design methods.

### 6.1 Model 1

Considering a second-order process transfer function as [20]

$$G_1(s) = \frac{e^{-10s}}{s(s+1)^2} \tag{25}$$

The IFODT model of Eq. (25) (with $CR = 0.1168$) is,

$$G_1(s) = \frac{e^{-10.87s}}{s(1.27s+1)} \tag{26}$$

PID Tuner provides three terms as: $k_p = 2$, $k_i = 0.01948$ and $k_d = 1.40078$. As per tuning equations provided by [34], the parameters of typical SP-SMC are: $\lambda_0 = 0.1744$, $\lambda_1 = 1.1811$, $k_d = 0.1955$ and $\delta = 1.4154$ while $p_d(s) = 0.302s + 0.0965$. Jaya optimization algorithm gives the

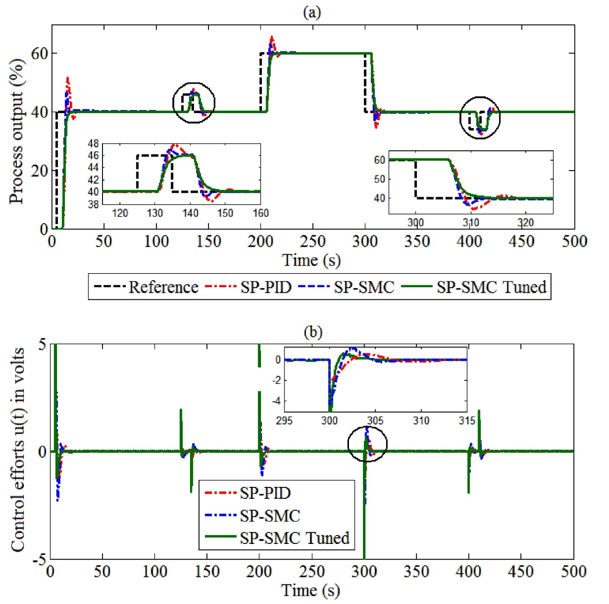


***Fig. 6**: Set-point change and disturbance suppression response. (a): Process output response y(t) and (b) Controller output u(t).*

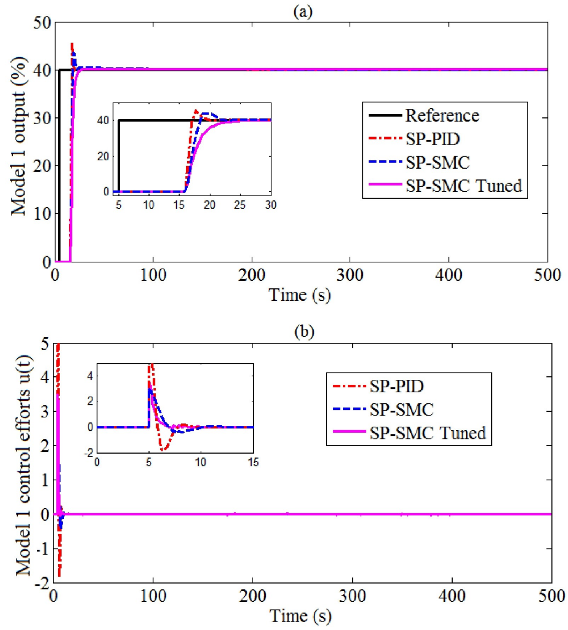


***Fig. 8**: Performance of $G_1(s)$ (Eq. 26). (a): System output response and (b): Controller output u(t).*

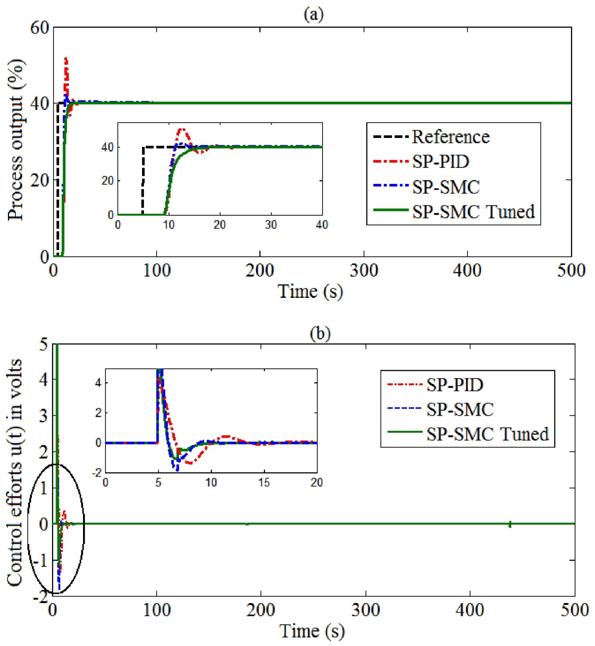


***Fig. 7**: Robustness test. (a): Output response y(t) and (b): Control efforts u(t).*

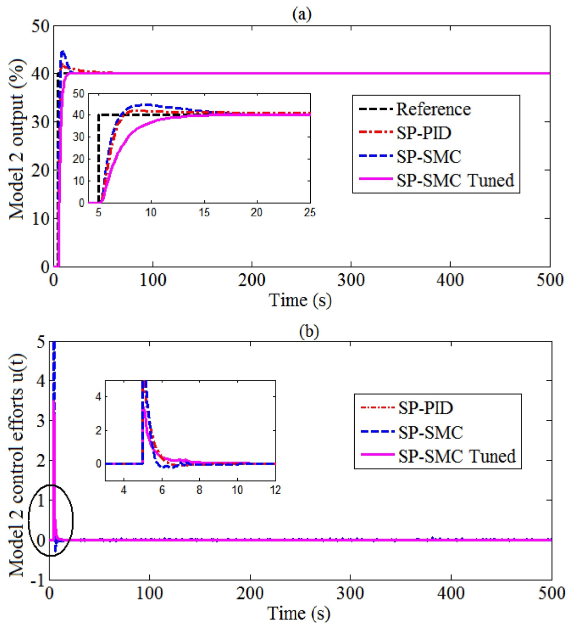


***Fig. 9**: Performance of $G_2(s)$ (Eq. 27). (a): System response and (b): Controller signal efforts u(t).*

parameters as $\lambda_0 = 0.01$, $\lambda_1 = 0.387$, $k_d = 3.8$ and $\delta = 0.2$ while $p_d(s) = 0.302s + 0.0965$. Fig. 8 (a) explores the performance of the system represented by Eq. (25), indicating the supremacy of the proposed design. Fig. 8 (b) shows the smooth learning curves of the controller output u(t). However, for Model 1, the delay in output response is 10 seconds, as shown in Fig. 8 (a). Table 7 depicts time-domain specifications obtained for Model 1. According to Table 7, with the proposed strategy, a zero percentage overshoot can be observed while the settling time and response speed are more than other methods.

### 6.2 Model 2

The efficiency of the proposed optimization technique is verified for the transfer function ($CR = 4$) [36].

$$G_2(s) = \frac{e^{-0.2s}}{s(0.8s+1)} \tag{27}$$

***Table 7**: Summary of time-domain specifications for Model 1.*

| Controller Type | $T_s(sec.)$ | $T_r(sec.)$ | $M_p(\%)$ |
|---|---|---|---|
| SP-PID | 21.2 | 2.6 | 3.5 |
| SP-SMC | 23.1 | 3.64 | 3.26 |
| SP-SMC Tuned | 23.25 | 3.26 | 0 |

***Table 8**: Summary of time-domain specifications for Model 2.*

| Controller Type | $T_s(sec.)$ | $T_r(sec.)$ | $M_p(\%)$ |
|---|---|---|---|
| SP-PID | 18.5 | 2.53 | 13.68 |
| SP-SMC | 14.6 | 2.273 | 2.89 |
| SP-SMC Tuned | 14.6 | 2.543 | 0 |

The PID controller parameters are revealed to be $k_p = 1.1$, $k_i = 0.05$, and $k_d = 0.5$ and the parameters of the SP-SMC design method $\lambda_0 = 3.125$, $\lambda_1 = 5$, $k_d = 2.150$, $\delta = 3.94$, and $p_d(s) = 0.7239(0.4s + 1)$. The Jaya optimization algorithm provides the following parameters: $\lambda_0 = 0.002$, $\lambda_1 = 0.42$, $k_d = 3.25$, $\delta = 0.159$, and $p_d(s) = 0.2896s + 0.7239$.

Fig. 9 (a–b) shows the estimated closed-loop response represented by Eq. (27) and related control signal effort. The superiority of the Jaya optimization algorithm can be observed in Fig. 9 (a–b) and Table 8, demonstrating the time-domain performances in terms of non-overshoot response and settling time. However, a slow response is demonstrated compared to the classical methods for Model 2.

## 7. CONCLUSIONS

In this study, the Jaya optimization algorithm is proposed for fine-tuning the SP-SMC parameters for better loop performance and robustness. The suggested technique is compared with typical SP-PID and conventional SP-SMC structures. The modeling of the laboratory process (level) control system is performed via the system identification toolbox of MATLAB R2014a using recorded input-output data. The IFODT model has been identified.

The simulation tests indicate that the proposed method exhibits an improvement of 19.7% and 22.93% in response speed over SP-PID, and SP-SMC strategies with 33.07% and 12.58% in settling time, respectively. Most importantly, it shows a zero percent overshoot in the closed-loop response. The proposed technique shows better invariance against 30% plant parametric uncertainty and external bounded disturbances. The results of the reference-point changes and disturbance rejection are more competent than other reported methods. It ensures convergence of the cost function in finite time as depicted in Table 4.

Besides, according to the simulation results for Models 1 and 2, in Tables 7 and 8, it is clear that the Jaya algorithm-based SP-SMC outperforms the prevalent strategies in terms of time-domain parameters and error-based performance indices. It shows better robustness and disturbance rejection capability. However, the selection of the cost function, lower bounds, and upper bounds of the controller parameters remains a challenge. Future work could include a strategy for more complex processes where large-scale datasets are needed to elevate the dead-time element. The proposed work may be an option for industrial applications where elevated dead time is present.

## ACKNOWLEDGMENTS

The authors are grateful to Dr. Vithalrao Vikhe Patil College of Engineering, Ahmednagar, India, for providing excellent research facilities and environment at the Electrical Engineering Department.

## CONFLICT OF INTEREST

The authors declared no potential conflict of interest with respect to research, authorship and/or publication of this research article.

## FUNDING

No financial support has been received for the research, authorship, and/or publication of this paper.

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