Design and experimental validation of normal terminal sliding mode control for level tank system

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Abstract: The paper explores the design of a normal terminal sliding mode controller (normal TSMC) for a nonlinear uncertain laboratory level tank system. The reachability condition of closed-loop system has been deduced from direct Lyapunov candidate function. The proposed design method has been compared with proportional, integral and derivative (PID) controller and typical sliding mode control (SMC). Normal TSMC and classical SMC are verified by using simulation as well as real-time experimentation while PID controller has been validated via experimental tests. The simulation and experimental result investigates that normal TSMC algorithm is more superior than PID and SMC strategies for estimated plant parameters, switching the set-point from one level to the other and internal, and external disturbances. It explores the better improvement in time-domain specifications such as response speed, settling time, overshoot in percentage, rise time and error performance indices.

Keywords: level tank system; normal terminal sliding mode control; proportional, integral and derivative controller; real-time experimentation.

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1 Introduction

Due to 'variability' of the processes, proportional, integral and derivative (PID) controller does not provide satisfactory performance though it is most commonly (about 95%) used in different process industries. Based on the type of processes and load variations, PID controller gains have to retune frequently to achieve the better performance. For elevated dead-time element in the process, it gives unsatisfactory response with low robustness (Seborg et al., 2006). With strong nonlinearities and multiple variable interactions, it provides a poor performance (Garrido et al., 2016).

To handle parametric uncertainties and system parameter perturbations, sliding mode control (SMC) is a prominant robust control strategy. It is dynamic behaviour depends on an appropriate switching function. The reaching condition and robust performance in an uncertain system are the key advantages of SMC (Utkin, 2020; Slottine and Li, 1991; Polyakov and Fridman, 2014) than robust adaptive method (Sastry and Bodson, 2011), H_2 and H_∞ control (Chen, 2020), and backstepping control techniques (Khalil et al., 2020). Presently, SMC has been implemented for various applications such as motion control, process control, robotics, power electronics and aerospace applications (Jeong et al., 2018; Sabanovic, 2011; Hung et al., 1993; Young, 1993; Utkin, 1992).

Though SMC technique is better against bounded uncertainties/disturbances and unmodelled dynamics (Slottine and Li, 1991; Hung et al., 1993; Utkin, 1992), it is basic configuration give rise to 'chattering' phenomenon which restrict it is use in practical applications. To alleviate/ eliminate chattering, researchers designed second-order SMC (Levant, 1993) and high-order SMC (Levant, 2001) in which relative degree is more than one.

In case of typical SMC, major limitation is that the system state takes infinite-time to reach at an equilibrium point or steady-state condition. Hence, the inspiration is that system states must reach to the equilibrium point in a finite-time, thereby other control strategy named as terminal sliding mode control (TSMC) (Venkatraman and Gulati, 1993). The limitations of typical SMC has been removed by using TSMC to different applications (Chen and Lin, 2010; Wang et al., 2016; Zheng et al., 2014; Jin et al., 2014; Incremona et al., 2017). It is well known that convergence of system states is slower if states are closer to an equilibrium point. The system dynamics with non-smoothness may lead to superior performance thereby introducing a terminal attractor. This leads to evolution of TSMC (Zak, 1988).

Chiu et al. (2012) explored TSMC for photovoltaic power system. The simulation and experimental result reveals the chattering reduction and parameter convergence as an expected results. Zhao et al. (2015) proposed output feedback TSMC for complex continuous stirred tank reactor for estimating the system states and stabilising output error to zero in a finite time. Simulation test validates the effectiveness of proposed method.

Recently, Ebrahimi et al. (2021) developed a model free higher-order TSMC for exoskeleton robot against parametric uncertain conditions and disturbances. The simulation and experimental result explores better performance of proposed control method while Chiu (2012) developed derivative and integral TSMC for multi-input multi-output (MIMO) systems. They accomplishes finit-time convergence for higher-order MIMO systems thereby avoiding singular problem and eliminating reaching time of sliding modes.

Behnamgol and Vali (2015) explored TSMC to a class of unmatched uncertain moving cart system with finite time stability. The reaching and sliding times in presence of both matched and unmatched uncertainty conditions have been conformed. The controller validation was done via simulation tests. Wu and Wang (2016) investigated a new finite time TSMC for hydroturbine governing system to control the vibrations. Numerical simulations were performed to elicit it is performance. Bembli et al. (2021) used TSMC approach to control an exoskeleton upper-limb. Stability and robustness have been verified using Monte carlo simulation. Simulation tests verifies effectiveness of the control signal.

Andemeskel and Semere (2018) developed a model-based designs for manufacturing system and it is accociated control strategy to improve classical system performance. They identified interactions and dependencies in the development process, and modelled the systems using SysML. The simulation tests validates proposed strategy while internet-based fuzzy control of cement production has been illustrated by Zermane and Mouss (2018). Using fuzzy control, they ensured the operation of cement mill with minimal downtime and used remote control system to diagnose the problems in a cement mill.

Bakhti et al. (2019) applied a robust integral backstepping control strategy with extended Kalman filter observer to a permanent magnet synchronous motors to estimate an accurate parameters such as speed, position, stator current and load torque. The stability of a system was analysed. The simulated results show efficacy of proposed method under parametric uncertainties and low speed.

The researchers (Laware et al., 2023a, 2023b) designed different control strategies to a process control problem. Authors designed an integral augmented SMC to improve the performance of level control plant. They ensured stability condition via Lyapunov candidate function and better closed-loop response for set-point changes, and applied external disturbances with 15% parametric uncertainties (Laware et al., 2023a). A real-life applicability of global SMC for uncertain tank system was verified based on minimum and maximum values of nominal system parameters to alleviate chattering effect by Laware et al. (2023b). They shown the efficiency of proposed strategy to second-order uncertain servo plant via simulation tests. The real-time experimentation and simulation results validates proposed control design method.

A demonstration of global optimisation algorithm to support vector machine (SVM) was carried out using particle swarm optimisation (PSO). Fuzzy logic technique was used to adjust the algorithm-specific parameters of PSO. The fuzzified PSO provides optimal parameters of SVM. The validation of proposed strategy was carried out for motion control of a robotic manipulator. The proposed control method outperforms the basic SVM and PSO-SVM in terms of tracking performance and reduced control efforts (Kapoor and Ohri, 2016). A non-singular TSMC was designed for maximum power tracking of wind energy system to ensure good tracking performance, less tracking error and fast response speed against wind speed variation (Karim et al., 2022).

The contributions of manuscript are as follows:

1. From the author's knowledge and literature survey, very few researchers have practically implemented TSMC strategy for process control applications. Most of the applications have been covered in the area of motion control.
2. Applicability of TSMC for level tank system as a process control application to investigate enhanced performance.
3. Comparison of proposed method to prevalent control designs.

The paper is structured as: Section 2 presents problem statement and motivation behind the manuscript. Section 3 presents controller designs while Section 4 explores the simulation and experimental test results. Finally, conclusion is presented.

2 Problem statement and motivation

2.1 Problem statement

The second-order nonlinear uncertain plant is (Slottine and Li, 1991; Laware et al., 2018),

$$\ddot{\zeta}(t) = -(a \pm \Delta a)\dot{\zeta}(t) - (b \pm \Delta b)\zeta(t) + (c \pm \Delta c)u(t) + B_d(t) \tag{1}$$

where $\zeta(t)$ is system output, $u(t)$ is the control input signal, a,b and c are estimated dynamics. Δa, Δb and Δc are deviations in the estimated system parameters. The term $B_d(t)$ denotes bounded disturbances.

One can write equation (1) as

$$\ddot{\zeta}(t) = -a\dot{\zeta}(t) - b\zeta(t) + cu(t) + B_d(t, u(t)) \tag{2}$$

where $B_d(t, u(t))$ is the uncertainty term which satisfies the condition $|B_d| \leq B_{d\,\max}$ and $B_{d\,\max} > 0$. One has,

$$B_{d\,\max} = \pm\Delta a\dot{\zeta}(t) \pm \Delta b\zeta(t) \pm \Delta cu(t) + B_d(t) \tag{3}$$

The lower bound of $B_{d\,\max}$ is selected as zero while upper bound of $B_{d\,\max}$ is given by (Laware et al., 2018)

$$B_{d\,\max} = +\Delta a|\dot{\zeta}(t)| + \Delta b|\zeta(t)| + \Delta c|u(t)| + |B_d(t)| \tag{4}$$

The expression for error is,

$$e(t) = i(t) - \zeta(t) \tag{5}$$

where $i(t)$ is an input signal and $\zeta(t)$ is measured output signal.

2.2 Motivation

It is well known that in a typical SMC, output error do not exactly converges to zero in a finite-time (Sastry and Bodson, 2011). However, due to linear attractor term in TSMC, the convergence of system state enhances, chattering decreases and reaching time gets eliminated (Wu and Wang, 2016). The purpose of proposed design is to ensure invariance against parameter perturbations, improved system performance and output error convergence to zero in a finite-time.

3 Design of controllers

3.1 PID controller

In this article, PID controller is experimentally validated whose time-domain representation is (Bequette, 2003),

$$u_{pid}(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \dot{e}(t) \tag{6}$$

where K_p, K_i and K_d are the three tuning constants of PID controller. However, the algorithm shown by equation (6) is not physically realisable. Hence, 'practical' PID algorithm has been selected as (Bequette, 2003)

$$u_{pid}(t) = k_p \left[\frac{\tau_i s + 1}{\tau_i s} + \frac{\tau_d s}{\tau_f s + 1} \right] \tag{7}$$

where τ_i, τ_d and τ_f are integral, derivative and filter time-constant respectively. The filter time constant has been selected as $\tau_f = \alpha \tau_d$ where α is 0.1 or less.

3.2 Typical sliding mode controller

For implementation of classical SMC, sliding surface is selected as (Utkin et al., 2020; Hung et al., 1993; Utkin, 1992)

$$\sigma(t) = \dot{e}(t) + (\beta_{smc})e(t) \tag{8}$$

β_{smc} is a positive constant, i.e., $\beta_{smc} > 0$.

Taking derivative of equation (8), substituting the expression from equation (5) as $\ddot{e}(t) = \ddot{i}(t) - \ddot{\zeta}(t)$ and considereing equation (1), an equivalent control signal for the tank system is,

$$u_{eq}(t) = -(c)^{-1}[a\dot{\zeta}(t) + b\zeta(t) + (\beta_{smc})\dot{e}(t)] \tag{9}$$

The total control input is addition of an equivalent control signal and discontinuous signal where the discontinuous signal is selected as (Slottine and Li, 1991; Sabanovic, 2011; Utkin, 1992)

$$u_{dis}(t) = (\alpha_{smc})sgn(\sigma(t)) \tag{10}$$

where $\alpha_{smc} > 0$ is the discontinuous gain factor. From equations (9) and (10), the total control signal to level tank is,

$$u_{smc}(t) = -(c)^{-1}[a\dot{\zeta}(t) + b\zeta(t) + (\beta_{smc})\dot{e}(t) + (\alpha_{smc})sgn(\sigma(t))] \tag{11}$$

3.3 Terminal sliding-mode controller

To control second-order system, sliding surface in basic TSMC is selected as (Venkatraman and Gulati, 1993; Ghogare et al., 2021)

$$s(t) = \dot{e}(t) + (\beta_{tsmc})^{(n/m)} \tag{12}$$

where β_{tsmc} is a design constant such that $\beta_{tsmc} > 0$. $0 < n/m < 1$. m and n are odd positive integers. For $e(0) \neq 0$ and $s = 0$, the dynamics of equation (12) approaches to zero in a finite time. Settling-time of TSMC is (Hongbin, 2018),

$$t_s = (\beta_{tsmc})^{-1}(1 - n/m)^{-1}|e(0)|^{(1-n/m)} \tag{13}$$

$e(0)$ is terminal attractor and the term $e^{(n/m)}$ improves finite time convergence towards an equilibrium point.

Taking the derivative of equation (12), substituting the expression as $s(t) = \dot{s}(t) = 0$ for reachability condition and without considering the uncertainty terms, one has an equivalent control signal as

$$u_{eq}(t) = -(c)^{-1}[\ddot{i}(t) + a\dot{\zeta}(t) + b\zeta(t) - B_{d\max}(t) + (n/m)(\beta_{tsmc})e(t)^{(1-n/m)}] \tag{14}$$

with discontinuous control input as (Slottine and Li, 1991; Laware et al., 2018)

$$u_{dis}(t) = (K_{tsmc})sgn(s(t)) \tag{15}$$

Hence, the total control input signal is addition of $u_{eq}(t)$ and $u_{dis}(t)$ which is,

$$u_{tsmc}(t) = -(c)^{-1}[\ddot{i}(t) + a\dot{\zeta}(t) + b\zeta(t) - B_{d\max} + (n/m)(\beta_{tsmc})(e(t))^{(1-n/m)} + K_{tsmc}sgn(s(t))] \tag{16}$$

3.4 *Stability analysis*

Applying control law of equations (15)–(16), one has,

$$\dot{s}(t) = B_{d\max} - (K_{tsmc})sgn(s(t)) \tag{17}$$

Consider Lyapunov candidate function to evaluate the convergence property as (Utkin et al., 2020; Utkin, 1992; Levant, 1993)

$$V(t) = \frac{1}{2}s^2(t) \tag{18}$$

With initial condition as a zero and $V(t)$ is positive definite function with the condition $s(t) \neq 0$.

Taking derivative of equation (18),

$$\dot{V}(t) = s(t)\dot{s}(t) < 0, s(t) = 0 \tag{19}$$

with $s(t)\dot{s}(t)$ negative definite function and putting equation (17) into equation (19),

$$\begin{aligned}\dot{V}(t) &= s(t)\dot{s}(t)\\ &= s(t)[(-K_{tsmc})sgn(s(t)) + B_d(t)]\\ &= -s(t)\left[(K_{tsmc})\frac{|s(t)|}{s(t)} + s(t)B_d(t)\right]\\ &= -(K_{tsmc})|s(t)| + |s(t)||B_d(t)|\\ &= -|s(t)|[B_{d\max} - K_{tsmc}]\end{aligned} \tag{20}$$

The equation (20) is negative semi-definite if and only if $(K_{tsmc}) \geq (B_{d\max})$. Also, it indicates that sliding surface selected approaches to zero in a finite time. The stability condition is $(K_{tsmc}) > 0$, $(K_{tsmc}) \geq (B_{d\max})$ and $(n/m) - 1 < 0$.

To reduce the chattering effect and increase of convergence speed hyperbolic tangential function is used as: $u_{dis}(t) = (K_{tsmc}) \tanh \frac{s(t)}{\Omega}$.

4 The simulation and real-time experimental results

The demonstration of normal TSMC, typical SMC and PID control design method has been carried out for laboratory level tank system used by Laware et al. (2018). The real-life experimental test setup is depicted in Figure 1. System is modelled via the process reaction curve method and identified process transfer function is,

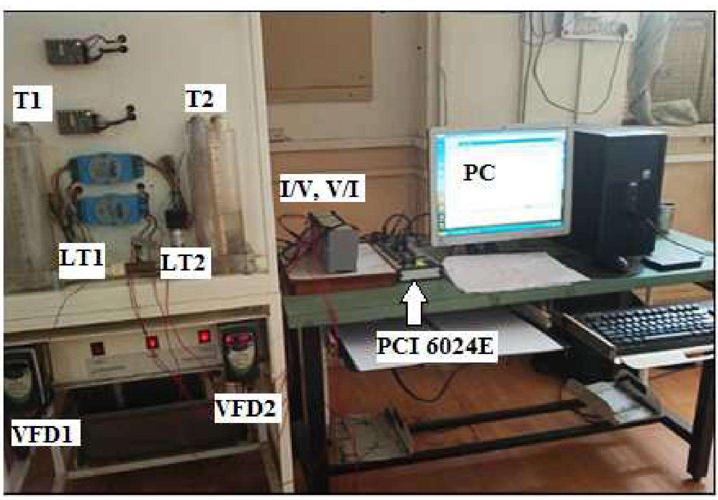
$$G_p(s) = \frac{\zeta(s)}{i(s)} = \frac{0.005}{(s^2 + 0.27s + 0.0062)} \tag{21}$$

The process reaction curve method is used to find the parameters of first-order plus dead-time (FOPDT) process model. The two point method II of PRC provides FOPDT model. From the step response curve, two times t_2 (at 63.2% of final steady-state value) and t_1 (at 28% of final steady-state value) are estimated respectively. The following relations provide a FOPDT model (Seborg et al., 2006).

$$\begin{aligned} K_{static} &= \zeta_\infty \\ \tau_p &= \frac{3}{2}[t_{63.2} - t_{28}] \\ \tau_d &= (t_{63.2} - T) \end{aligned} \tag{22}$$

where K_{static}, τ_p, τ_d are the static gain of process, time-constant of process and dead-time of process respectively.

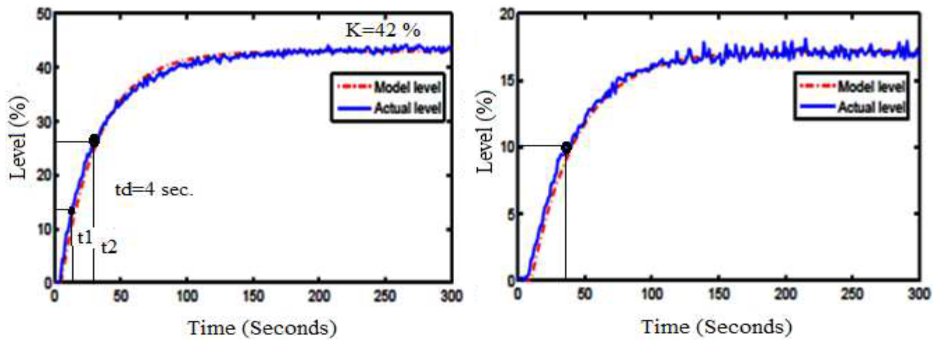
Figure 1 Real-time experimental setup (see online version for colours)



Source: Laware et al. (2023a)

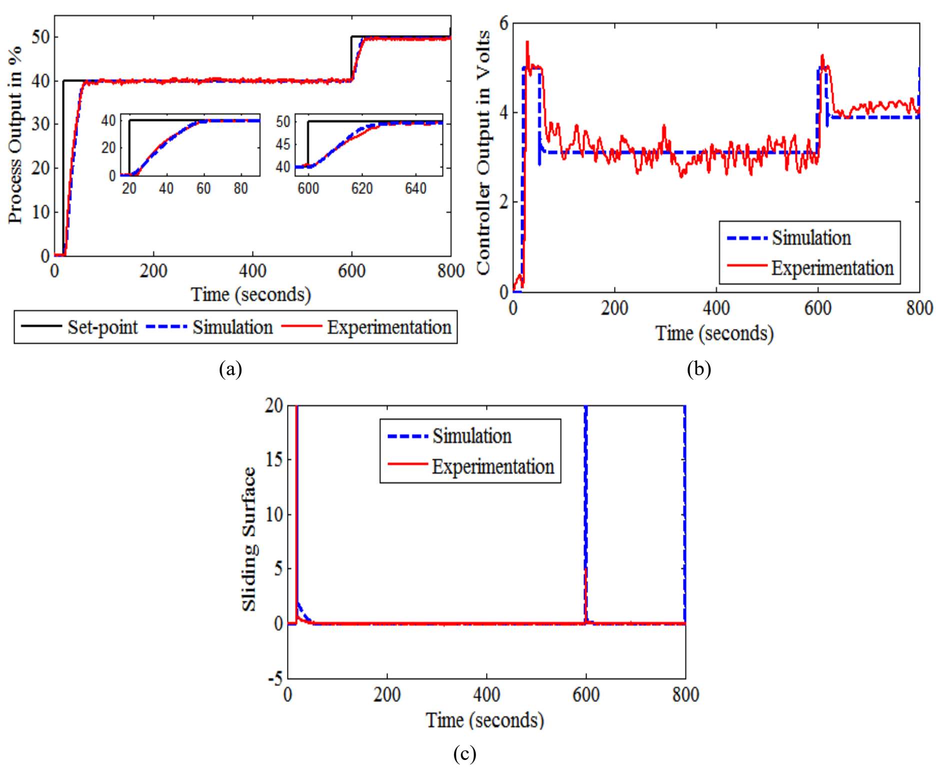
Experimental output of model and actual output are depicted in Figure 2 once 3.5 V has been applied to the pump. Figure 2 shows open-loop step test for recorded input-output data. The FOPDT model is derived from 40% level. The model has been verified for different level (17% level). The estimated parameters as: a = 0.27, b = 0.0062 and c = 0.005.

Figure 2 Open-loop test (see online version for colours)



Source: Laware et al. (2023b)

Figure 3 Process response of normal TSMC, (a) nominal response (b) controller output in volts (c) variation of sliding surface (see online version for colours)



Equation (21) is validated for simulation and real-time experimentation. Figures 3(a)–3(c) devises the nominal performance of normal TSMC strategy with associated variations of sliding surface and control efforts required to drive the process output variable to a set-point value. Figure 3(a) illustrates the nominal response upto 600 seconds. For normal TSMC, the process output (level) settles to a reference value of 40% at about 55.2 seconds. After 600 seconds, the reference point has been switched from 40% to 50%. For reference-point change response, normal TSMC outperforms as compared to SMC and PID designs. Figure 3(b) shows the trends of controller output in volts. As observed from Figure 3(b), initial magnitude (experimental) of control effort is 5.8 volts while it deviates between $\pm$ 1.32 volts. Figure 3(c) indicates the sliding surface which converges to zero at about 65 seconds. In Figures 3(a)–3(c), exact at 800 seconds, a disturbance of 1% is applied. The variation of controller output in volts and sliding surface $s(t)$ is depicted in Figures 3(b) and 3(c).

Figure 4 Process response of SMC, (a) nominal response (b) controller output (c) variation of sliding surface (see online version for colours)

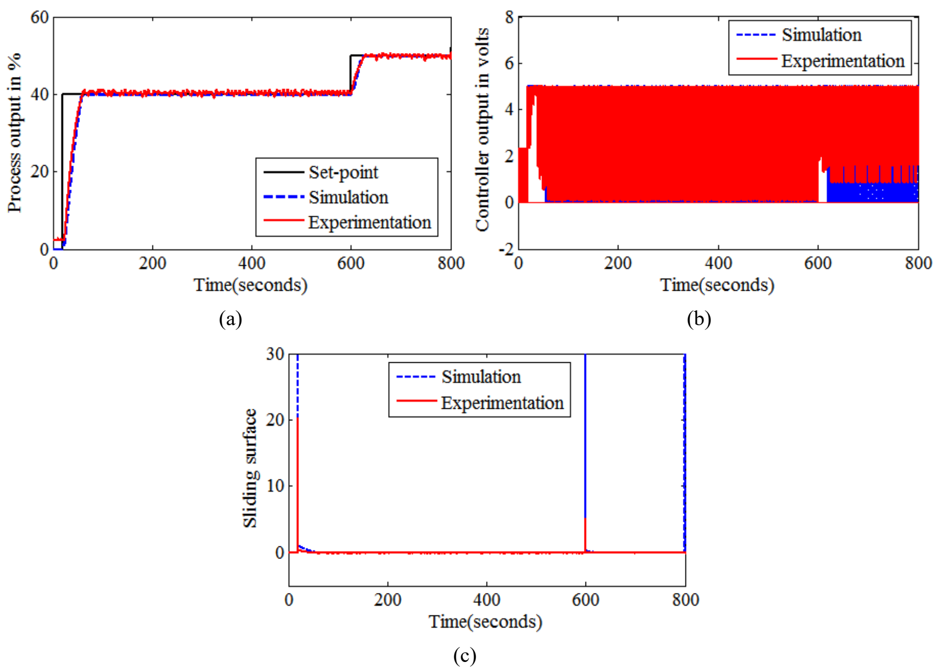
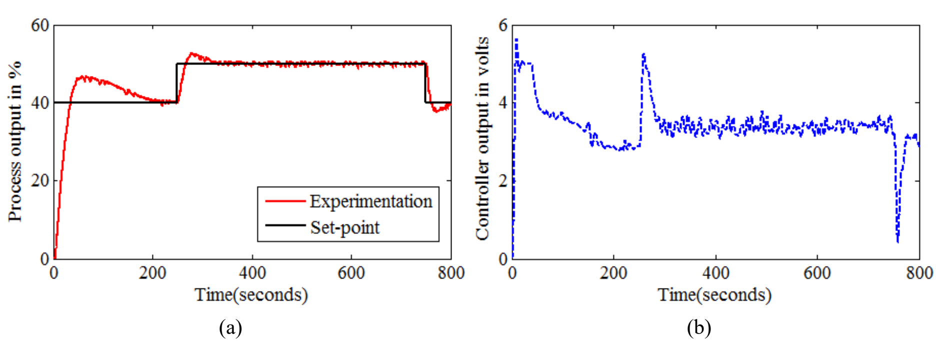


Figure 5 Process response of PID controller, (a) nominal response (b) controller output (see online version for colours)



Figures 4(a)–4(c) explores the performance of conventional SMC for nominal system parameters, multi-level set-point change with associated control efforts. Figure 4(a) indicates that process variable reaches to a set-point at about 65.3 seconds. It shows $\pm$ 0.6% deviation in output response. Figure 4(b) indicates 'chattering effect' of classical SMC. The control signal chatters between 0-5 volts which causes serious pre-mature wear and tear of an actuator. Figure 4(c) shows variation of sliding surface $s(t)$ which converges to zero in a finite-time of 76 seconds. Figures 4(a)–4(c) depicts the trends of response for 1% applied disturbance at 800 second.

Figures 5(a)–5(b) depicts experimental process response for PID controller. As seen from Figure 5(a), up to 250 seconds, it illustrates the estimated response. 8.5% overshoot and long settling time of 201.5 seconds have been observed in process output. A reference-point has been changed from 40% to 50% for the period 250–750 seconds. The process output is with more fluctuations and overshoot. Figure 5(b) depicts the variations in control signal. It shows more variations in controller output.

Table 1 illustrates time-domain specifications such as settling time T_s, rise time T_r, % overshoot M_p and error-based performance indices like integral absolute error IAE, intergral square error ISE, and mean square error MSE. Table 2 tabulates performance improvement of normal TSMC over reported classical control design techniques in percent (%).

Thus, from Figures 3, 4, 5, Tables 1 and 2 it is observed that normal TSMC is well competent over SMC and PID strategies in terms of time-domain specifications and error-based performance indices. The sliding surface and error signal converges earlier to zero in normal TSMC.

Parameter selection: The parameters for normal TSMC method are selected as: n = 3, m = 1, β_{smc} = 0.2, K_{tsmc} = 3.2 and Ω = 0.2 while the parameters of typical SMC are: β_{smc} = 0.2 and α_{smc} = 3.2. The three terms of PID controller have been selected as K_p = 1.1, K_i = 0.09, K_d = 0.001 and α = 0.1. The selection of above parameters is based on heuristic strategies.

The performance improvement of normal TSMC over SMC in settling time, rise time, % overshoot, IAE and ISE is 15.46%, 15.18%, 75%, 3.93%, 3.83%, and 37.29% respectively while over PID strategy, the performance improvement is 72.6%, 23.4%, 97.6%, 9.45%, 15.14%, and 52.0% respectively. The sliding surface and the error signal converges earlier to zero.

Table 1 Performances of controller

Controller type	T_s	T_r	M_p	*IAE*	*ISE*	*MSE*
Normal TSMC	55.2	32.4	0.2	75.7	45.89	0.227
SMC	65.3	38.2	0.8	78.8	47.72	0.362
PID	201.5	42.3	8.5	83.6	54.08	0.473

Table 2 Performance improvement of normal TSMC over SMC and PID control design methods in percent (%)

Controller type	T_s	T_r	M_p	*IAE*	*ISE*	*MSE*
SMC	15.46	15.18	75	3.93	3.83	37.29
PID	72.6	23.4	97.6	9.45	15.14	52.0

5 Conclusions

In this study, normal TSMC is been designed to enhance the overall performance of level tank system. Direct Lyapunov candidate function determines the stability condition of a system. The process reaction curve method is used to derive the FOPDT model of process. The comparison has been made based on time-domain specifications and error-based performance indices.

Simulation and experimental tests shows the superiority of normal TSMC design over classical SMC and PID methods. Proposed design ensures the invariance property for the reference-point change. The reference-point following capability of proposed design is better over the prevalent techniques. From the results tabulated in Tables 1 and 2, it can be seen that normal TSMC strategy significantly improves the control performance of tank system. It shows the better convergence of sliding surface (and hence error signal) to zero in a finite-time interval.

Normal TSMC strategy may consider for industrial applications where non-overshoot response is desired. The applicability of normal TSMC may find where fast response speed and less settling time is required. Singularity and complex value problems are the limitations of normal TSMC design. For the future work, limitations as stated above needs to examine and implementation to MIMO system needs to be validated.

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