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Adaptive robust PID sliding control of a liquid level system based on multi-objective genetic algorithm optimization*

by

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Abstract: Adaptive robust PID sliding mode control optimized by means of multi-objective genetic algorithm is presented in this paper to control a three-tank liquid level system with external disturbances. While PID constitutes a reliable and stable controller, when compared to sliding mode control (SMC); robustness and tracking performance of SMC are higher than those of the PID control. To use the unique features of both controllers, optimal sliding mode control is executed in terms of a supervisory controller to enhance the performance of optimal adaptive PID control and to provide the necessary control inputs. After the design of the control law, control coefficients of all four involved controllers are optimized by using the multi-objective genetic algorithm so as to minimize errors and the input of the controller. Simulations illustrate that the adaptive robust PID sliding controller based on multi-objective genetic algorithm optimization provides a superior response in comparison to the results obtained separately by PID control, sliding mode control, and adaptive PID control, respectively.

Keywords: sliding mode control, PID control, adaptive control, genetic algorithm, multi-objective optimization, liquid level system

1. Introduction

Since liquid level systems have numerous practical applications in industry, control of such systems has attracted researchers' interests, primarily with respect

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to the design of novel optimal robust control laws. Indeed, the designed controllers need to apply an appropriate voltage to a pump so as to control the rate of flow, and make the outflow rate proportional to the height. To control the liquid level systems, researchers have utilized and developed appropriate controllers (see Fan and Xia, 2000; Ramli et al., 2009; Li et al., 2009; Iplikci, 2010; Yu et al., 2013), specifically, type-1 and type-2 fuzzy control (see Engin et al., 2004; Cosenza and Galluzzo, 2011), adaptive control (see Pan and Wang, 2006), neural network control (see Li et al., 2008), and fractional order PI control (see Narayanaswamy et al., 2010; Sundaravadivu et al., 2011). PID constitutes a robust controller in the context of controlling the liquid level systems. Shengduo and Xiaolong (2012) established a control system based on programmable logic controller (PLC) by the PID algorithm, and this control system can adjust the liquid level automatically, when PLC obtains the liquid height through the sensing circuit and then it determines the PID parameters in the framework of an automatic adjustment mode. Kayacan and Kaynak (2006) proposed a grey prediction based on high accuracy - without knowing the mathematical model - fuzzy PID controller to handle a non-linear liquid level system. They illustrated that the controller has the ability to control the non-linear system precisely with little overshoot and no steady-state error. Mehta et al. (2011) proposed the IMC (internal model control) tuned PID algorithm to control the liquid level control systems. Liang (2011) applied the fuzzy PID control approach to the coupled-tank liquid-level control system with a lumping lag and nonlinear characteristics.

To enhance the capability of PID controllers, researchers have combined this type of controllers with other ones, such as H_∞ control (see Ho, 2003; Saeki, 2006; Goncalves et al., 2008; Kim et al., 2008; Toscano and Lyonnet, 2009; Alcantara et al., 2011), fuzzy control (see Song et al., 2013; Wang and Ma, 2012; Li et al., 2012; Yuhua and Jianlin, 2012; Zhang et al., 2012; Cetin and Akkaya, 2010; Sang and Han, 2014; Wang and Li, 2012), and neural network control (see Cho, 2009; Yu and Yin, 2012; Zhu et al., 2012; Wang et al., 2012; Kwan Ahn and Cong Thanh, 2005; Fang, 2010; Chen and Lin, 2013). Apart from many unique advantageous features of PID control, i.e. simple design and easy application, PID control has inferior tracking performance when compared to sliding mode control. Zhao et al. (2015) developed and used terminal sliding mode control for a continuous stirred tank reactor. Orlowska-Kowalska et al. (2014) used sliding mode control to design the direct control of the induction motor torque. They could achieve the unified design process of the control system and the estimator. On the other hand, when considering reliability and stability, PID control can operate with high performance when compared to sliding mode control (see Cao and Chen, 2012; Hao et al., 2011; Cao and Chen, 2013; Mirhassani et al., 2013; Andrecioli and Engeberg, 2012). In this regard, the present study tends to utilize the hybrid setting of PID control and sliding mode control to employ the advantages of both controllers for the control of the liquid level system. Some research studies utilized the benefits of the hybrid setting of these two controllers, as follows. Choi and Lee (2009) proposed a PID based sliding mode controller using an observer to prevent the lateral movement of strips in the hot rolling process and also solved the chattering problem of sliding mode control. Shi et al. (2011) developed a double surface sliding mode PID controller that can further improve the dynamic and static characteristics of the drilling rotary system. They demonstrated that the proposed controller has good robustness with respect to the uncertainties of rock formation and drilling string and it enhances the stability and reliability of the system.

While a number of researchers have used the trial-and-error process to find the parameters of nonlinear controllers, it must be indicated that the trial-and-error process is a poorly justified and generally not sufficiently reliable approach, which is inappropriate for the selection of the coefficients of the controllers. To ascertain those parameters and move beyond the trial-and-error procedure, swarm algorithms and evolutionary techniques can be employed. Swarm algorithms, such as particle swarm optimization (see Mahmoodabadi et al., 2013b, 2014a, 2014b), ant colony optimization (see Castillo and Melin, 2012; Castillo, 2012), and bee colony optimization (see Chang, 2013; Rajasekhar et al., 2011a; 2011b; Sabura Banu and Uma, 2010); as well as evolutionary algorithm techniques, including genetic algorithm optimization (see Andalib Sahnehsaraei et al., 2013; Xiao et al., 2011) and genetic programming (see Dracopoulos and Effraimidis, 2012), have been used to design the parameters of the controllers based on optimization approaches. Some studies have included research on the advantages of the combination of those algorithms, such as the hybrid of particle swarm optimization and genetic algorithm optimization (see Mahmoodabadi et al., 2013b) and the combination of ant colony optimization and genetic algorithm optimization (see Unal et al., 2013). Recently, Boscariol et al. (2011) proposed a constrained model predictive control system as an effective control approach for position and vibration control of a flexible links mechanism. They illustrated the effectiveness of the method by using exhaustive numerical simulations.

This research extends authors' work (see Mahmoodabadi et al., 2014a, 2014b; Andalib Sahnehsaraei et al., 2013) by proposing adaptive robust control, which is based on the combination of PID control and sliding mode control. To this end, sliding mode control in combination with PID control is developed and used to control the liquid level system in order to provide a proper tracking performance as well as proper reliability and stability. To choose the parameters of the controller, multi-objective genetic algorithm optimization is utilized to design the controller based on the design criteria. Eventually, PID, SMC, Adaptive PID, and the proposed method, optimized by multi-objective genetic algorithm optimization are applied to the liquid level system, subject to challenging external disturbances.

2. The liquid level system with external disturbances

The liquid level system having demanding external perturbations is considered in the present investigation as a practical engineering control problem, and is treated by the optimal adaptive robust PID sliding mode control. The schematic drawing in Fig.1 represents the model of the system, which is composed of three tanks connected to each other. The three tanks have the same diameters and the outflow of tank 1 becomes in feed to tank 2, and the outflow of tank 2 is in feed to tank 3.

The differential equation of the system is as follows:

$$a\dddot{q}_{output} + b\ddot{q}_{output} + c\dot{q}_{output} + dq_{output} = q_{input} - q_{dis} - C_1R_1\dot{q}_{dis} \tag{1}$$

Then, the state space equations of the system will be as follows:

$$\dot{q}_1 = q_2 \tag{2}$$

$$\dot{q}_2 = q_3 \tag{3}$$

$$\dot{q}_3 = [u(t) - \delta(t) - b * q_3 - c * q_2 - d * q_1]/a \tag{4}$$

$$y = q_1 \tag{5}$$

where $u(t) = q_{input}$ is the control input, $q_1 = q_{output}$, $q_2 = \dot{q}_{output}$, and

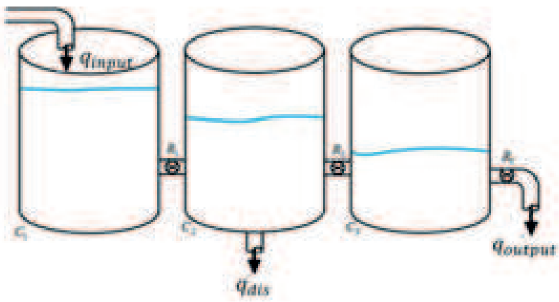

Figure 1. The liquid level system with three tanks connected

$q_3 = \dot{q}_{output}$. δ (t) is external disturbances. δ (t) and the coefficients in Eq. (4) are as follows:

$$a = C_1C_2C_3R_1R_2R_3 \tag{6}$$

$$b = C_1C_2R_1R_2 + C_1C_2R_1R_3 + C_1C_3R_1R_3 + C_1C_3R_2R_3 + C_2C_3R_2R_3 \tag{7}$$

$$c = C_1R_1 + C_1R_2 + C_1R_3 + C_2R_2 + C_2R_3 + C_3R_3 \tag{8}$$

$$d = 1 \tag{9}$$

$$\delta(t) = q_{dis} + C_1R_1\dot{q}_{dis} \tag{10}$$

where $R_1 = 2$, $R_2 = 1$, $R_3 = 1.5$, $C_1 = 1.2$, $C_2 = 1$, $C_3 = 0.8$, and q_{dis} is as follows.

$$q_{dis} = \begin{cases} 0 & if \;\; t \leq 1.05 \;\&\; t \geq 2.05 \\ 5 & if \;\;\;\;\;\; 1.05 \leq t \leq 2.05 \end{cases}$$

3. Sliding mode control

Sliding mode control (SMC) is a robust control, in which adjustment of the dynamics of a nonlinear system is performed by the application of a discontinuous control signal, which makes the system slide along a cross-section of the system's normal behavior (see Zinober, 1990; Slotine and Li, 1991). Indeed, the sliding mode control is a variable structure control approach, in which switches can occur from one continuous structure to another, based on the current position in the state space. In SMC, the ultimate trajectory is not realized within one control structure and the actual trajectory will result from sliding along the boundaries of the control structures.

Considering a non-linear system in the general state space, we can write as follows:

$$\dot{q} = f\left(q, u, t\right) \tag{11}$$

where $x \epsilon R^n$ represents the state vector, $u \epsilon R^m$ stands for the input vector, n represents the order of the system and m is the number of inputs. Then the sliding surface $s\left(e, t\right)$ is as follows:

$$s\left(e, t\right) = \left\{e : H^T e = 0\right\} \tag{12}$$

where $H \epsilon\, R^n$ denotes the coefficients or slope of the sliding surface. Here,

$$e = q_{output} - q_d = q_1 - q_d \tag{13}$$

is the negative tracking error vector.

The sliding surface $s\left(t\right)$ is defined in the state-space R^n by the scalar equation, as follows:

$$s\left(e, t\right) = \left(\frac{d}{dt} + \lambda\right)^{n-1} e = 0 \tag{14}$$

where λ is a strictly positive constant and it can be explained as the slope of the sliding surface.

The sliding surface s for the system of the present study (a third order system) is defined according to Eq. (15):

$$s\ \left(e, t\right) = \left(\frac{d}{dt} + \lambda\right)^2 e = \lambda^2\left(q_1 - q_d\right) + 2\lambda\ \left(q_2 - \dot{q}_d\right) + \left(q_3 - \ddot{q}_d\right) \tag{15}$$

The n^{th}-order tracking problem is now being replaced by a 1^{st}-order stabilization problem, where the scalar s is to be maintained at zero by a governing reaching condition. By considering the Lyapunov function $V\left(q\right) = \frac{1}{2}s^2$, the fulfillment of the reaching condition is guaranteed by Eq. (16) (see Jing and Wuan, 2006).

$$\dot{V}\left(q\right) = s\dot{s} < 0. \tag{16}$$

The sliding mode of the system response tends to chatter along $s = 0$. Taking into account Eq. (16), the existence and convergence condition is re-written as follows:

$$s\dot{s} \leq -\eta s. \tag{17}$$

Eq. (17) guarantees the existence of a non-switching region. Here, η is a strictly positive constant. The value of η is selected on the basis of knowledge of disturbances or system dynamics in the aspect of some known amplitudes. In this control approach, by changing the control law according to certain pre-defined rules, depending on the position of the error states of the system with respect to sliding surfaces, the states are switched between stable and unstable trajectories until they reach the sliding surface (see Ng et al., 1995).

It can be shown that the sliding condition of Eq. (16) is always satisfied by:

$$u_{SMC} = u_{eq} - k\, sat\,(s) \tag{18}$$

$$u_{eq} = \delta\,(t) + d\,q_1 + (c\, - a\,\lambda^2)q_2 + (b - a\,\lambda)\,q_3 + a\,\lambda^2 \dot{q}_d + a\,\lambda\,\ddot{q}_d + aq_d \tag{19}$$

where u_{eq} is called equivalent control input obtained by setting $\dot{s} = 0$. k represents a design parameter and $\eta \leq k$, while function $sat(.)$ is illustrated in Fig. 3.

The function sgn causes extreme frequency chattering in sliding mode control and a discontinuity occurs in the controller. To diminish the frequency in the control input, a thin boundary layer around the sliding surface is defined as follows:

$$B\,(t) = \{x; |s\,(q)| \leq \phi\}. \tag{20}$$

The chattering can be excluded (Fig. 2) by smoothing the discontinuity in the control law across the boundary layer. One appropriate approach to eliminate the discontinuous portion of the control law is to utilize the linear interpolation across the boundary layer. This is accomplished by defining a boundary layer of thickness ϕ and substituting the function sgn with the function $sat\,(s/\phi)$ as follows (Fig. 3):

$$sat\,(\phi) = \begin{cases} sgn\,(s/\phi) & if\ |s/\phi| \geq 1 \\ (s/\phi) & if\ |s/\phi| < 1 \end{cases}. \tag{21}$$

4. PID control

A proportional-integral-derivative controller (PID controller) is a generic control loop feedback controller with extensive applications in industry. This controller may be regarded as an extreme form of a phase lead-lag compensator with one

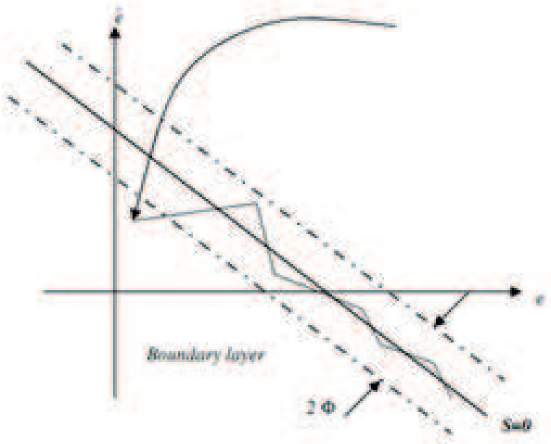

Figure 2. The schematic view of sliding plant for a smooth controller

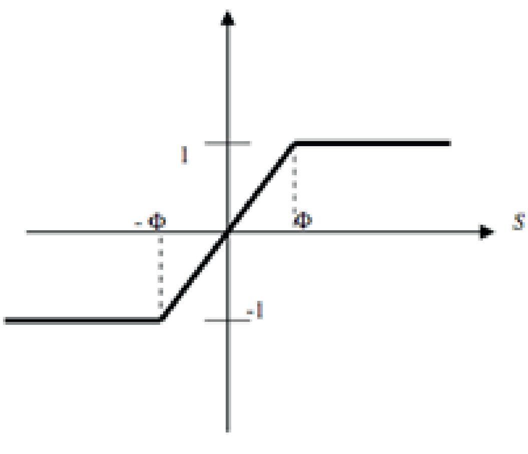

Figure 3. Function $sat\,(s/\phi)$

pole at the origin and the other at infinity. It computes the error as the difference between a measured process variable and a desired set point, and minimizes the error by regulating the process control input. It is sometimes called three-term control, since it has three separate constant parameters: the proportional (P), the integral (I), and the derivative (D) coefficients. These values can be interpreted in terms of time, that is, P depends on the present error, I on the accumulation of past errors, and D is a prediction of future errors, based on current rate of change. The weighted sum of these three actions is employed to regulate the process such as the position of a control valve, a damper, or the power supplied to a heating element.

The standard form of the control input of the PID controller is mostly written in the form of Eq. (22).

$$u_{PID}(t) = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{d}{dt} e(t) \tag{22}$$

where $e = q_d - q_{output}$ and K_p stands for the proportional gain, K_I is the integral gain, and K_D is the derivative gain. Indeed, the function of the proportional term is to supply an overall control input proportional to the error signal through the all-pass gain factor. The role of the integral term is to diminish the steady-state errors through low-frequency compensation by the integrator. The function of the derivative term is to increase the efficiency of transient response through high-frequency compensation by the differentiator. The analysis of the parameters of PID control of the closed-loop system is presented in Table 1 (see Ang et al., 2005). It can be seen from Table 1 that when K_D increases, the stability diminishes. This fact has been supported by the implementation of PID control in industry as well as by academic analyses. However, it has been seen that the increase of K_D may cause the reduction of stability in case a transport delay exists (see Li et al., 1998; Quevedo and Escobet, 2000).

Table 1. The analysis of the parameters of PID control

The parameters of PID control	Overshoot	Rise time	Stability
Enhancing K_p	Augmentation	Diminution	Diminution
Enhancing K_I	Augmentation	Minor Diminution	Diminution
Enhancing K_D	Diminution	Minor Diminution	Augmentation

5. Optimal adaptive robust PID sliding mode control

Adaptive control is the approach utilized in the context of designing a controller, which must adapt to a controlled system with parameters which change, or are initially uncertain. While adaptive control is concerned with changing control laws, the robust control laws do not need to be changed if the changes in the system remain within the given bounds, i.e. the bounds on uncertain or time-varying parameters. For instance, as an aircraft flies, its mass will slowly diminish due to fuel consumption. Hence, a control law is needed that adapts itself to such changing conditions. Common approaches to estimation of parameters of adaptive control involve recursive least squares and gradient descent. In the present research, the gradient descent as an appropriate adaptation law is utilized to update three gains of PID control based upon sliding mode control (see Chang and Yan, 2005). In case the sliding mode happens, the sliding surface must be $s = 0$. The gradient descent and the chain rule are utilized to obtain the adaptation laws for three control gains of K_p, K_i, and K_d, as follows (see Chang and Yan, 2005):

$$\dot{K}_p = -\gamma_p \frac{\partial S\dot{S}}{\partial K_p} = -\gamma_p \frac{\partial S\dot{S}}{\partial u_{pid}} \frac{\partial u_{pid}}{\partial K_p} = -\gamma_p s e \tag{23}$$

$$\dot{K}_i = -\gamma_i \frac{\partial S\dot{S}}{\partial K_i} = -\gamma_i \frac{\partial S\dot{S}}{\partial u_{pid}} \frac{\partial u_{pid}}{\partial K_i} = -\gamma_i s \int_0^t e(\tau) d\tau \tag{24}$$

$$\dot{K}_d = -\gamma_d \frac{\partial S\dot{S}}{\partial K_d} = -\gamma_d \frac{\partial S\dot{S}}{\partial u_{pid}} \frac{\partial u_{pid}}{\partial K_d} = -\gamma_d s \frac{de}{dt} \tag{25}$$

where γ is a positive value. In case the parameters of the controller are not chosen appropriately, the controller cannot work correctly. However, the supervisory controller is applied to deliver a sufficient input u_{SMC} according to Eq. (18). The overall control input including the PID control input and sliding mode control input is computed according to Eq. (26):

$$u = u_{PID} + u_{SMC}. \tag{26}$$

The block diagram of the optimal adaptive robust PID sliding mode control is illustrated in Fig. 4.

Because the proposed control scheme is a linear combination of the adaptive PID and sliding mode controllers, it is expected that the proposed strategy have a better performance in comparison with each of the sole controllers. In fact, since in the application of the optimal adaptive robust PID sliding mode control, the best controller from both PID control and sliding mode control, providing minimum error and control inputs, is chosen at every instant of the time, the overall performance would be superior when compared to the single controllers, realizing either PID or sliding mode control.

6. Multi-objective genetic algorithm optimization

To design the parameters of the controller, multi-objective genetic algorithm (GA) optimization, being an adaptive search technique, mimicking the process of evolution, is utilized in the present investigation. In the genetic algorithm, a population of candidate solutions (called individuals, creatures, or phenotypes) to an optimization problem is evolved toward better solutions. When GA is applied to a problem, it uses some kind of genetics-based mechanism to iteratively create new solutions from the currently available ones. Then, it substitutes some or all of the existing solution population members with the recently produced members. The aim of this approach is to improve the quality of solutions with the passing of time. A straightforward genetic algorithm involves individual selection from population, based on the fitness, the individuals being produced from the preceding population thorough crossover and mutation, with consideration of definite probabilities when producing new individuals.

In case the designer needs to account for several objective functions, a multi-objective optimization algorithm, which is also referred to as multi-criteria optimization or vector optimization is required to find a vector of decision variables values, satisfying constraints, to secure acceptable values regarding all the objective functions (see Deb et al., 2002).

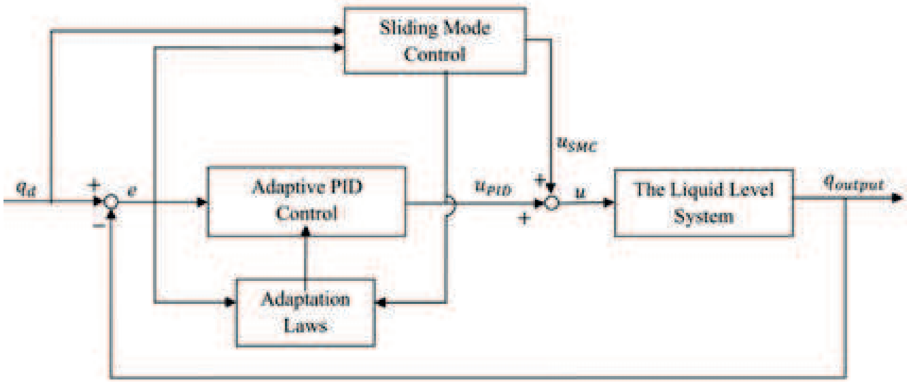

Figure 4. The block diagram of the optimal adaptive robust PID sliding mode controller

In this study, the multi-objective genetic algorithm of the Global Optimization Toolbox of "MATLAB R2013a" is used in order to determine the optimal parameters of the proposed controller.

In this paper, the vector $[K_p\, K_i\, K_d,\, k,\, \lambda,\, \gamma_p,\, \gamma_i,\, \gamma_d]$ is the vector of the design variables (selective parameters) of the controller. k is a positive constant and λ is the coefficient of the sliding surface. This is a multi-objective optimization problem having two objective functions, according to Eqs. (27) and (28):

$$f_1 = \int_0^T |e(t)|\, dt \tag{27}$$

$$f_2 = \int_0^T |u(t)| \, dt. \tag{28}$$

The intervals of values of $K_p\, K_i\, K_d$, γ_p, γ_i and γ_d are taken between -10 and 200. The values of k and λ are assumed to vary between 0 and 200.

7. Results of the optimal adaptive robust PID sliding mode control

The Pareto front, obtained on the basis of multi-objective genetic algorithm optimization for the optimal adaptive robust PID sliding mode controller and three other controllers is illustrated in Fig. 5. All the optimum design points in the Pareto front elucidated in that figure are "non-dominated", meaning that no better ones can be found, and can be chosen by the designer based upon the design criteria. There are some crucial optimal design observations in the case of these two objective functions, which have been established by the Pareto optimum design approach. Naturally, if any other set of decision variable values is selected, the corresponding values of the pair of the objective functions considered will define a point inferior to any point, located on the Pareto front. By regarding the first objective function, the best feasible point for the Pareto of each controller is selected to find their associated design variables [???]. Point A represents the optimal point of the PID controller, chosen from the Pareto front of the PID controller. Point B stands for the optimal point of the SMC controller, selected from the Pareto front of the SMC controller. Point C is the optimal point of the adaptive PID controller, chosen from the Pareto front of the adaptive PID controller. Point D corresponds to the optimal point of the here proposed controller, chosen from the Pareto front of the controller.

The design variables and objective functions, corresponding to the optimal design points A, B, C and D are illustrated in Table 2. The input, output, and error values for those controllers are shown in Figs. 6-8. The results illustrate the fact that the controller performance is appropriate, as it is a hybrid controller, using the advantages of adaptive PID control and sliding mode control. In the here reported investigation, the proposed approach yielded a better Pareto front, providing smaller values of both objective functions, as shown in Fig. 5. Furthermore, the proposed controller displays better characteristics, such as lower settling time, when compared to other three controllers, this fact being illustrated in Fig. 6. As it is clear from that figure, there is no overshoot for each of the four controllers. Moreover, the minimum error of the optimal adaptive robust PID sliding mode controller is less than for all three other controllers, as shown in Fig. 7.

8. Conclusions

This study presented the adaptive robust PID sliding mode control, optimized by multi-objective genetic algorithm for controlling a three-tank liquid level

Table 2. The objective functions and the associated design variables for the optimum points, illustrated in Fig. 5

Optimum design aspect	Method Applied			
	PID	SMC	Adaptive PID	Proposed method
Design variable K_p	25.49	-	-	-
Design variable K_i	-0.36	-	-	-
Design variable K_d	56.52	-	-	-
Design variable k	-	5.8771	-	33.9461
Design variable λ	-	0.9404	4.3473	1.1515
Design variable γ_P	-	102.69	6.2289	-
Design variable γ_I	-	-	114.9439	-2.4323
Design variable γ_D	-	-	36.6832	12.1654
Objective function f_I	20.11	14.45	20.41	16.13
Objective function f_2	3.899	3.187	3.948	1.833

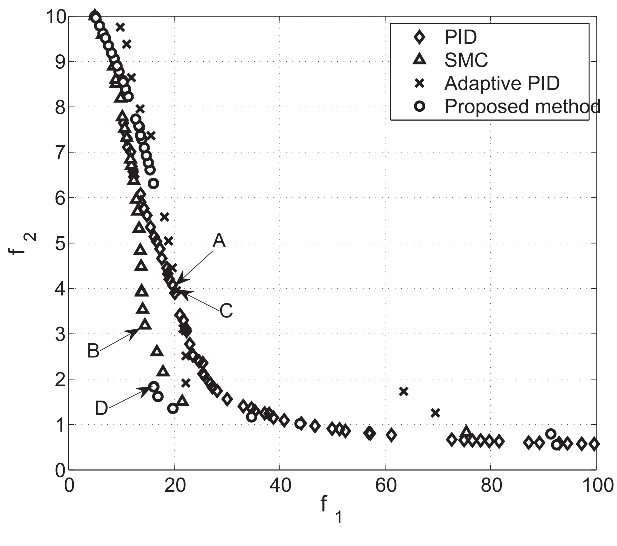

Figure 5. The Pareto front of the optimal adaptive robust PID sliding mode controller and three other controllers for the liquid level system

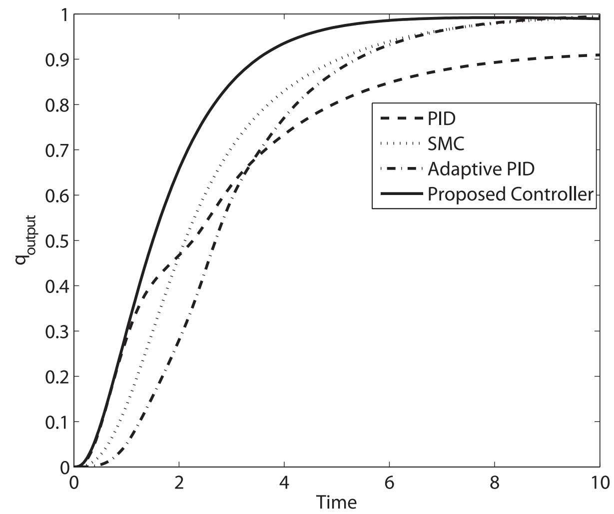

Figure 6. The output for the optimal adaptive robust PID sliding mode controller and three other controllers for the liquid level system having external disturbances

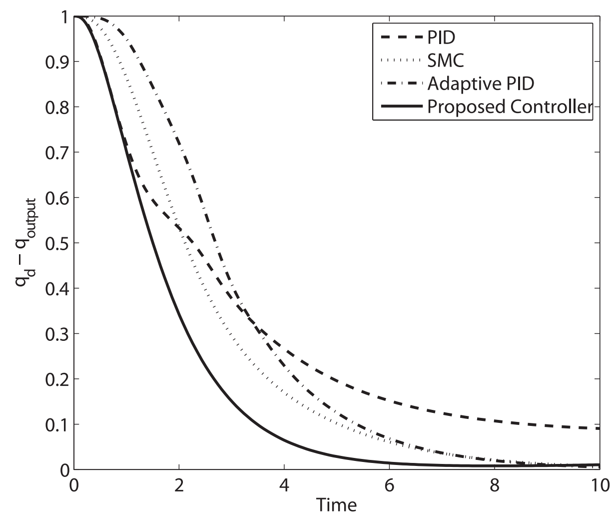

Figure 7. The error for the optimal adaptive robust PID sliding mode controller and three other controllers for the liquid level system having external disturbances

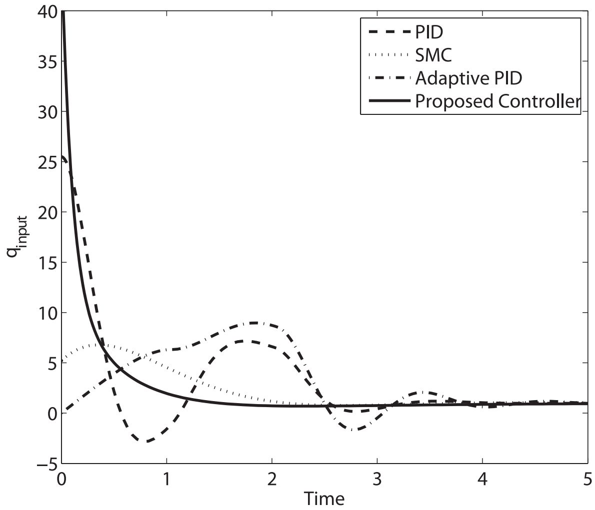

Figure 8. The input for the optimal adaptive robust PID sliding mode controller and three other controllers for the liquid level system having external disturbances

system. More precisely, optimal sliding mode control was employed as a supervisory controller to improve the performance of optimal adaptive PID control and provide sufficient control inputs. Indeed, PID controllers benefit from easy implementation, reliability and stability; however, SMC controllers are robust in the case of presence of disturbances and perturbations. A three-tank liquid system, subject to significant external disturbances is regarded as an intellectual challenge in industry, and is being addressed here by the proposed controller and three other controllers. Multi-objective genetic optimization algorithm was employed to design the optimal parameters of the controller, based on the design criteria. The performance of the control approach was compared to three controllers, i.e. PID control, sliding mode control and adaptive PID control, optimized by multi-objective genetic algorithm. Comparison of the proposed controller with the three other controllers demonstrates that the performance of the proposed controller for a three-tank liquid level system with external disturbances is superior as it has the least error and appropriate control inputs.

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