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IFAC PapersOnLine 51-13 (2018) 656–661

Tuning Parameters Optimization Approach for Dynamical Sliding Mode Controllers

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Abstract: This work proposes a tuning parameters optimization approach for Dynamical Sliding Mode Controllers developed from a reduced model using optimization criteria and restrictions which are given by performance factors that the process must reach. Simulations are carried on a nonlinear system with variable delay previously develop in Baez et al. (2017), and the controllers in this previous work are compared against a DSMC with this new tuning proposal using the ISE performance index.

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Keywords: Tuning, Optimization, Restrictions, Dynamical Sliding Mode Control, Integral Square Error.

1. INTRODUCTION

Within the control proposals there is one that has been widely used due to great robustness, it is the Sliding Mode Control (SMC) theory Utkin (1977). This variable structure control was subsequently develop from a First Order Plus Dead Time (FOPDT) model in Camacho and Smith (2000) with the aim of having a simple structure that can be easily used in an applicative way. In this approach, the sigmoid function is used in the discontinuous part of the controller in order to eliminate chattering. These high frequency oscillations are a problem in the control signal because they are changes that can generate fast dynamics that were not considered in the system modeling Guldner and Utkin (2000).

An alternative proposal to reduce this negative effect is the use of Dynamical Sliding Mode Controllers (DSMC) Sira-Ramírez (1992b) with the advantage of maintaining performance on the controller because a smoothing function is no longer used. This controller has been successfully tested in chemical reactors Sira-Ramírez (1992a), vertical flight regulation Sira-Ramirez et al. (1994), and wind driven induction generators De Battista et al. (2000), thus verifying its great performance.

A DSMC approach using the FOPDT model was developed in Proaño et al. (2017) to obtain a simple controller with fixed structure, it was tested in a high delay system, later it was compared against the SMC on a nonlinear system with variable delay Baez et al. (2017).

On one hand, results in both works show chattering reduction, and the second work a considerable improvement compared to the SMC. On the other hand, when high disturbances appear, the delay time increases, causing large modeling errors that generate oscillations on the response. In both works a tuning method is not used, but rather a heuristic searching which is not incorrect, yet insufficient because the best possible values are not being used.

There are several works to obtain tuning parameters for SMC, we can mention the research by Rojas et al. (2004), in this work they presented a SMC controller with tuning equations for open loop unstable systems where equations presented by Camacho and Smith (2000) were modified to satisfy process performance. Mohammad and Ehsan (2008) presented a chattering free sliding mode control (SMC) for a manipulator robot including a PID part with fuzzy tunable gain, later Piltan et al. (2012) presented the design of a controller for nonlinear uncertain dynamical systems. The result is a chattering free mathematical error-based tuning sliding mode controller (MTSMC), and it is also applied to a manipulator robot. Kose et al (2014) proposed an approach based on genetic algorithms to improve performance of the voltage stability of a power system with a static var compensator. The optimum values of the sliding mode controller and proportional-integral-derivative (PID) coefficients that are required are calculated using the GA technique. Mehta and Rojas (2017) offered a tuning method that has been used in a Smith Predictor based on Sliding Mode for unstable systems using the cuckoo optimization algorithm, Rajabioun (2011). Their proposal tries to minimize the Integral Square Timer Error (ISTE) and the signal variation of the controller.

As can be seen in the previous works, all the approaches have been done for SMC, in this work an optimization proposal to get the tuning parameters for a DSMC is studied. The optimization criterion is based on the Integral Square Error (ISE) considering additionally the settling time and the overshoot. These multiple performance factors are added as restrictions such a way the tuning values obtained let the output process reach or keep on the reference value with the best possible response.

This work is organized as follows: section 2 covers the basic concepts of the controllers and section 3 explains the tuning method proposed. Then, section 4 shows the simulation results between the DSMC with and without

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10.1016/j.ifacol.2018.07.355

the tuning method against the SMC to finally end with the conclusions of this work.

2. BASIC CONCEPTS

2.1 Sliding Mode Control

The sliding mode controller is widely know due to its robustness against inaccuracies in the process model and large disturbances. The objective is to bring the initial system state to a known desired behavior defined by a sliding surface.

The sliding mode control has two parts: the continuous one (U_C) makes the system being on the sliding surface causing the output mounting the reference, and the discontinuous part (U_D) is responsible for reaching the sliding surface at any moment Camacho (1996) (Fig. 1). Its control law is described next.

$$U(t) = U_C(t) + U_D(t) \tag{1}$$

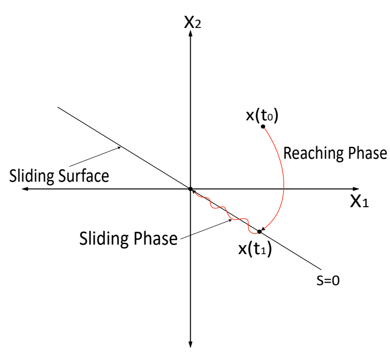

Fig. 1. SMC

2.2 Dynamical Sliding Mode Control

The proposed controller has been developed in Proaño et al. (2017) and studied too in Baez et al. (2017). This section shows the variation made in the controller to remove k_p of the control law, the elimination of this parameter does not affect the final performance, so the final sliding surface results in the next expression.

$$S(t) = e^{-}(t) + \lambda \int e(t)dt \tag{2}$$

Where:

$$e^{-}(t) = R(t) - X_m^{-}(t) \tag{3}$$

The term $e^{-}(t)$ is the difference between the reference and the output of the lead-lag transfer function (Fig. 2). Resulting the DSMC controller in:

$$\dot{U}(t) = \frac{\tau\lambda}{Kt_f}e(t) + \frac{1}{Kt_f}X_m^{-}(t) - \frac{1}{t_f}U(t) + k_D sign(S(t)) \tag{4}$$

The previous equation can be represented with the next structure.

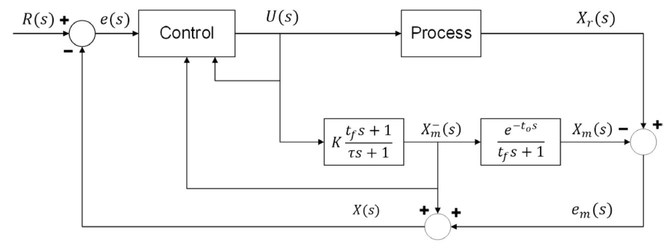

Fig. 2. DSMC Controller

Where:

$R(s)$	Reference	$U(s)$	Controller Output
$X_r(s)$	Process Output	$X_m^{-}(s)$	Invertible Part Output
$X_m(s)$	Model Output	$X(s)$	Total Output
$e_m(s)$	Modeling error	$e(s)$	Overall Error

Equation (4) was developed using deviation variables, so the next considerations have to be done to use the control law with a process that has initial conditions.

$$m(t) = \overline{m} \pm U(t) \tag{5}$$
$$m(t) = X_m^{-}(t) - \overline{TO} \tag{6}$$

Where $m(t)$ is the final controller output and $\overline{m}$ its initial condition. $\overline{TO}$ is the initial condition of the transmitter process output. Both possibilities in (5) depend on the static gain sign (K) of the process; this consideration also affects the sliding surface.

$$S(t) = sign(K) \cdot S(t) \tag{7}$$

Taking into account the last considerations, the final equations to be used are:

$$m(t) = \overline{m} \pm \int \left[\frac{\tau\lambda}{Kt_f}e(t) + \frac{1}{Kt_f}\left(X_m^{-}(t) - \overline{TO}\right) - ... \right.$$
$$\left. ... - \frac{1}{t_f}U(t) \right] dt + \int \left[K_D sign(S(t))\right] dt \tag{8}$$

$$S(t) = sign(K)\left[e^{-}(t) + \lambda \int e(t)dt\right] \tag{9}$$

3. TUNING METHOD

Once the controller is developed, the next step is to find its parameters to obtain the best performance, this procedure in most common controllers is done through tuning equations, but for the proposed controller there are not any of them, therefore, this next methodology can be used as a replacement.

It starts by selecting the tuning parameters, and a range of variation is defined in each one of them since in many occasions certain values produce instability which is not convenient in any control system. Next, the performance factors that will be used for comparison between the possible results are defined; in this work, the following ones have been selected: ISE, overshoot, settling time and chattering. The next step is the process simulation with all the chosen parameters, and the data store of the performance factors in each test.

For the DSMC controller, the following conditions were chosen.

Table 1. Performance Conditions

ISE	$M_p(\%)$	t_s	Chattering
ISE_{smc}	2 %	$2{\cdot}ts(FOPDT)$	1 %

One main DSMC objective is to obtain a better performance than the SMC, this means that the ISE of the DSMC has to be lower than the SMC ISE, reason why this value is selected. Furthermore, it is expected to have an overshoot value of less than 2%, a settling time less than two times the first order plus dead time model settling time and the control signal does not exceed a 1% chattering. It is clear that systems do not act in the same way, so these values can be redefined for the specific process under study.

The controller simulations with every selected parameter are translated into Fig. 3 which shows the dynamic behavior of the system in each test. The performance conditions in Table. 1 are translated to flat surfaces in Fig. 3. Besides, there are points over the flat surfaces, this means that some parameters do not accomplish the established conditions and in particular those that are above them have to be discarded because they do not reach the set requirements.

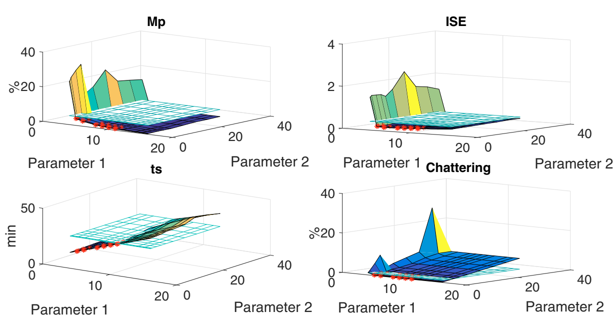

Fig. 3. Performance factors with parameter variations

Analyzing the previous figure, it may happen that the surfaces do not cut, in other words that the performance factors will not be reached with any parameter combination; in this case the level of demand towards the controller under study can be reduced.

Up to now, if any of the found parameters is chosen, it should be enough because the output is within the desired behavior, but to make a better choice an optimization process has been carried out by assigning weights to each performance factor in order to give more importance to the most critical. This can be represented with the following expression.

$$J = min\left(\sum_{i=1}^{n} c_i x_i\right) \tag{10}$$

Where n is the number of performance factors (x_i) considered, and c_i are the weights given to each factor, that is, the importance level that it has on the output, being 1 the maximum, thus:

$$\sum_{i=1}^{n} c_i = 1 \tag{11}$$

It can be noticed that the units in Table 1. are different, so a per unit change is made in each one of them where 1 is the maximum ISE, Mp, ts and chattering that has been obtained from among the possible parameters that reach the performance conditions.

Having all the ideal parameters with the corresponding weight allocation, it is proceed to choose those that provide the minimum value of J (Fig 4).

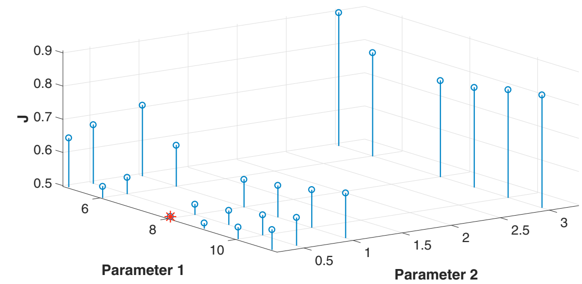

Fig. 4. Minimum J

Fig 3 and Fig 4 show a graphical explanation of this method, so it is not necessary to develop them for the tuning process when there are more than two parameters. In this work the parameters that intervene in the continuous part of the controller have been grouped because they affect almost completely in the output process.

When a single parameter is analyzed, the method remains the same, the difference is that there will be curves that get cut and not surfaces. Table. 2 shows the weights used in the tuning process.

Table 2. Optimization Weights

Parameters	Optimization
$t_f \mid \lambda$	$J = 0.4 \cdot ISE + 0.3 \cdot t_s + 0.3 \cdot M_p$
k_D	$J = 0.4 \cdot ISE + 0.2 \cdot t_s + 0.4 \cdot Chattering$

The λ parameter was obtained depending on λ_1 of the SMC controller.

$$\lambda = K_\lambda \cdot \frac{\tau + t_o}{\tau t_o} \tag{12}$$

Likewise, k_D has been obtained as a proportion of its counterpart in the SMC controller.

$$k_D = K_d \cdot \frac{0.51}{|K|}\left(\frac{\tau}{t_o}\right)^{0.76} \tag{13}$$

Where K_λ y K_d are proportional values.

4. SIMULATION RESULTS

The proposed study case has been developed in Camacho and Smith (1997, 2000) and used in Baez et al. (2017). Refer to one of them to see all its characteristics. The process consists of a mixing tank having two inlet flows, a hot and a cold one, the mixture produced is sensed at a distance of 125 ft from the tank; control is performed through the opening or closing of a valve which handles the amount of cold flow entering the tank (Fig. 5). Disturbances appear in the hot inlet flow.

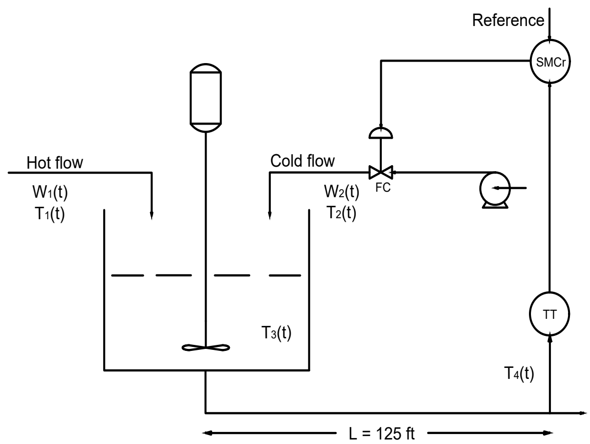

Fig. 5. Mixing tank

The FOPDT model used for control tuning is:

$$G(s) = \frac{-0.82}{2.2s+1}e^{-4.11s} \tag{14}$$

The DSMC controller has three tuning parameters (4), so the two of them (t_f and K_λ) that affect more in the output have been grouped. It has to be emphasized that chattering has not been evaluated with these parameters because its variation depends almost completely on the value of k_D.

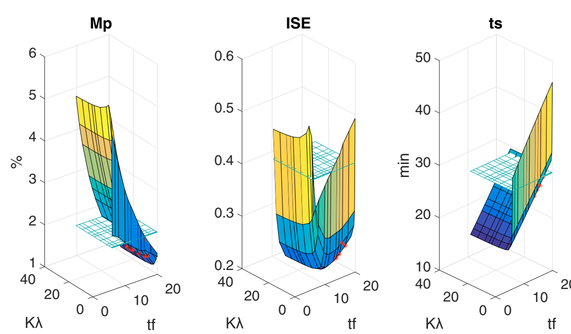

Fig. 6. Performance factors with t_f and K_λ

The previous figure shows that the dynamic behavior of the system is mostly determined by the variation of t_f. Then, the optimization process is done to select the best parameters. (Fig. 7).

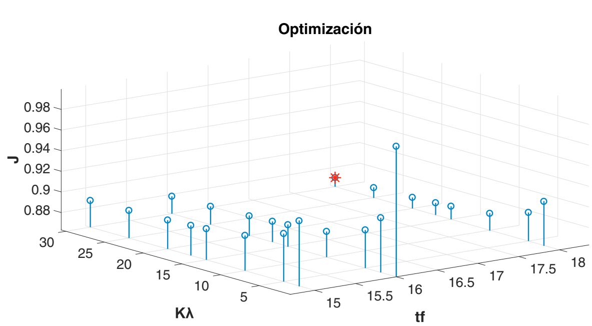

Fig. 7. Optimization of t_f and K_λ

Once the first parameters have been selected, k_D is evaluated; the M_p performance factor has not been analyzed because its variation is minimum.

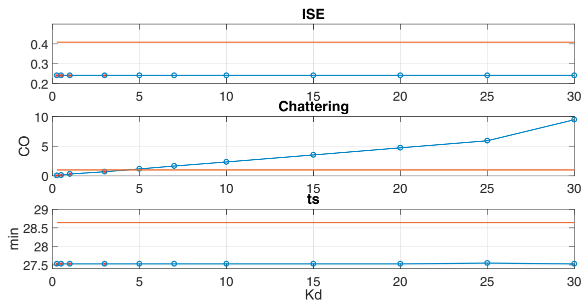

Fig. 8. Performance factors with K_d

Fig. 8 shows that k_D mainly affects the chattering, and to choose its best value the optimization process is done again (Fig. 9).

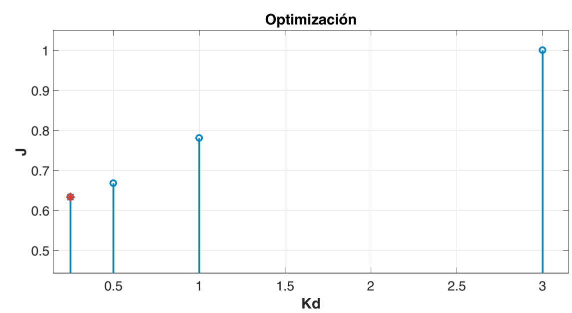

Fig. 9. Optimization of K_d

The final DSMC parameters are shown next in Table. 3.

Table 3. DSMC Parameters

	No Tuned	
t_f	λ	k_D
11	11.78	0.387
	Tuned	
t_f	λ	k_D
18	$30 \cdot \frac{2.2+4.11}{2.2+4.11} = 20.81$	$0.25 \cdot \frac{0.51}{\lvert 0.82\rvert}\left(\frac{2.2}{4.11}\right)^{0.76} = 0.097$

The SMC is performed in Camacho and Smith (2000).

Fig. 10 shows the system against delay variations through inlet flow rate changes. Only in the first disturbance, the DSMC without the tuning method reaches the reference in a shorter time than the others. Moreover, this controller has a faster action, but with greater oscillations which are related to the resulting modeling error. With the proposed tuning method, a reduction in overshoot is obtained.

Fig. 11 shows that the system dynamic behavior affects the control signal as well. As seen, both DSMC control signals are similar, but the overshoot reduction also decreases oscillations in the controller (Fig. 11). Chattering was satisfactorily reduced below the 2% barrier in a previous work Baez et al. (2017), nevertheless, with the proposed tuning method it is possible to reduce this value even more; 0.00075 compared to SMC (0.239) which represents less than 0.5% (Fig. 12).

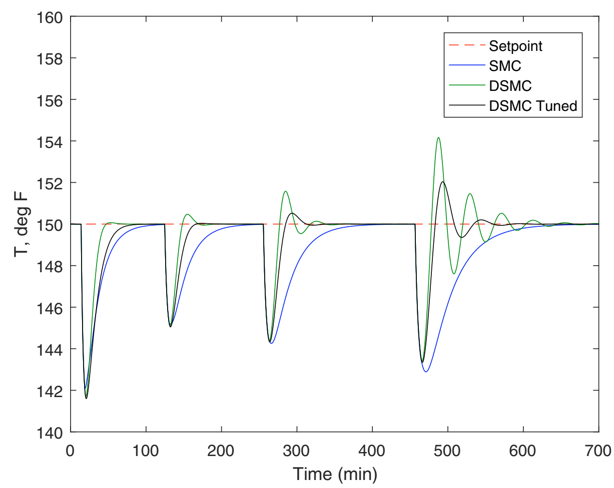

Fig. 10. Output Process

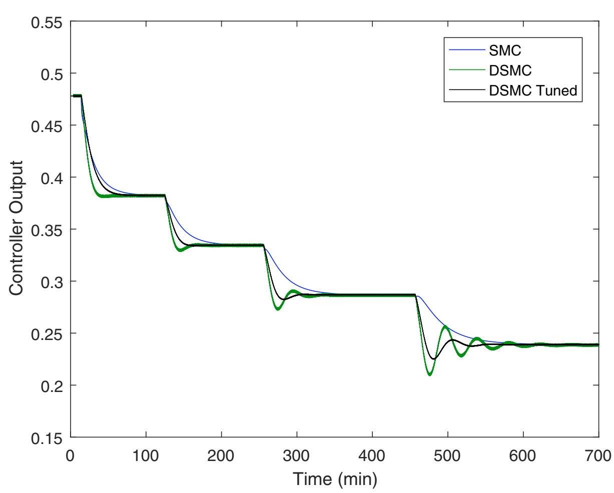

Fig. 11. Control Signal

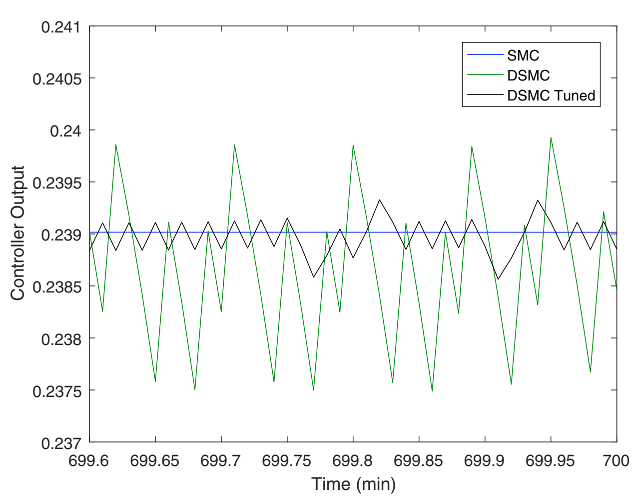

Fig. 12. Chattering in Control Signal

To compare every controller between each other, the ISE (Integral Square Error) performance index is used (15). The overall results are shown in Table. 4

$$ISE = \int_0^\infty e^2(t)dt \tag{15}$$

Table 4. ISE Comparison in initial conditions

SMC	**DSMC**	**DSMC Tuned**	**∆%**	**∆Tuned%**
0.3878	0.2041	0.2301	47.37	40.66

Even though the tunning approach shows a little lower performance than the normal DSMC, both controllers exceed the SMC.

There is a problem in the DSMC when high-value disturbances appear because they cause modeling errors which generate oscillations in the output. Thus, an analysis is performed only for the largest disturbance (Table. 5).

Table 5. ISE Comparison with 100% disturbance

SMC	**DSMC**	**DSMC Tuned**	**∆%**	**∆Tuned %**
1.34	1.372	1.0631	-2.43	20.58

Results show that big disturbances can cause a bad performance in the DSMC controller if it is not well tuned.

5. CONCLUSION

Simulation results show that the proposed method works well with small disturbances, but it really stands out when the worst conditions are given, ie when the delay has a 100% variation; in this case the non tuned DSMC controller is surpassed by the SMC, but using the proposed method it is possible to reduce oscillations making the DSMC Tuned the best performance.

As a result, it is not necessary to retune the parameters of the controller when different conditions of operation appear.

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