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Sliding Mode Controller Design with Optimized PID Sliding Surface using Particle Swarm Algorithm

Chong Chee Soon, Rozaimi Ghazali, Hazriq Izzuan Jaafar, and Sharifah Yuslinda Syed Hussien

***Abstract*— This article deals with an evaluation on the designed controller named as sliding mode control (SMC) which sliding surface of the controller has been integrated with proportional-integral-derivative (PID) controller. The control scheme is established from the derived dynamic equation which stability is proven through Lyapunov theorem. In the performance assessment on the designed PID sliding surface, the controller parameter is first obtained through conventional tuning method known as Ziegler-Nichols (ZN), which is then compared with the particle swarm optimization (PSO) computational tuning algorithm. From the observation of the simulation results, the PSO tuning algorithm showing outperform performances compared to the conventional ZN tuning method in term of trajectory tracking on the electro-hydraulic actuator (EHA) system.**

***Keywords*— PID Sliding Surface, Sliding Mode Control, Particle Swarm Optimization, Electro-hydraulic Actuator System.**

I. INTRODUCTION

In the past decades, electro-hydraulic actuator (EHA) system has been widely used especially in various heavy engineering works. The dynamics generated from the electrical motor of the system pumping the fluid under a certain velocity, which will provide the necessary pressure to a particular work such as clamping, lifting, and forming [1]. The combination of hydraulic, electric, and electronic components offers a massive improvement in the development of various applications. Due to the capability in delivering high forces with high energy density, EHA system became widely used in the industry field.

However, the issues of uncertainties and nonlinearities are usually facing by the EHA system, which concurrently yielding great challenges in the development of the control system implemented in the EHA system. Unsatisfied system performance will be appeared if inappropriate control strategy is applied whether in the positioning tracking capability or in delivering the force, which is often interfere by the disturbances for instance the friction and the leakage in the mechanism of the EHA system [2].

Numerous methods have been proposed against the existing issues, especially pointed in the development of the robust control system to overcome such uncertainties, variation in the system parameters, and disturbances. A wise and proper control approach will be needed in dealing with the complexity and the challenges in the control of the EHA system.

In the past decades, different classes of control approach have been found in the literature, in the implementation toward the difficulties in the control of EHA system. The raised numbers of works conducted with the control of the EHA system have been proposed ranged from linear control, nonlinear control to intelligent control strategies such as generalized predictive control (GPC) [3], model reference adaptive control (MRAC) [4, 5], sliding mode control (SMC) [1, 6], self-tuning Fuzzy proportional-integral-derivative (PID) [7, 8], and neural network (NN) [9]. In the literature study of [1], SMC control strategy is observed to have a good potential and widely implemented in the EHA system.

The SMC nonlinear control is verified to have a capability to maintain the control stability in various model that exposes to the disturbances and variations in the system parameters [10]. Due to its capability, SMC has been extensively implemented into various engineering applications such as active suspension system [11], pneumatic systems [12] and active magnetic bearing systems [13]. In the literature of [14], the sliding surface has been improved by adding an integral action which is simultaneously enhanced the tracking performance of the SMC control on the electromechanical plant.

This paper continues the work done in [15] where, the SMC control has been augmented with PID sliding surface for the purpose of enhancing the position tracking performance of the EHA system. The servo valve and hydraulic actuator integrating with the nonlinear dynamics model has been derived. Afterward, the SMC control scheme has been implemented in the system which stability of the control system is theoretically proven by Lyapunov theorem. Subsequently, the controller tracking performance has been compared to the optimized controller to demonstrate the significant improvement of the controller through the proposed technique.

The paper is organized as below. Section 2 describes the developed mathematical model of the EHA system. The implementation of SMC algorithm and PSO algorithm are explained in Section 3. The comparison within classical

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controller and proposed controller are presented in Section 4. Lastly, Section 5 is the conclusion of the study.

II. Modelling EHS System

An electrical current that delivered to the coil which mounted to the servo-valve produced a dynamic motion to the spool valve. The motor that received the electrical power source will generate the dynamic to the servo spool valve to switch to the desired position. The configuration of typical electro-hydraulic servo (EHS) system consists of hydraulic actuator and servo valve as demonstrated in Fig. 1.

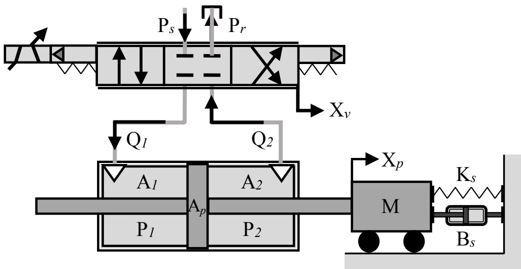

Fig. 1. The schematic of the EHA servo-valve.

Servo valve that producing the flow of fluid through the pipeline that creating dynamic motion to the hydraulic cylinder. The damper and spring mounted to the mass at the end of the actuator will generate a counter force to the hydraulic cylinder actuator.

An electrical current producing torque to the hydraulic pump that generating dynamics motion to the servo valve will be represented by a second order differential equation as indicated in the equation (1), [16].

$$\frac{d^2x_v}{dt^2} + 2\xi\omega_n\frac{dx_v}{dt} + \omega_n{}^2 = I\omega_n{}^2 \tag{1}$$

where the damping ratio represented in ξ, and the servo valve natural frequency represented in ω_n

In the design of each port in the spool valve, exposure of the dead-zone problems and the flow leakages are avoided. The spool valve condition is considered in the critical centred position. The servo valve that controls the flow rate, Q in the chamber can be formed through the equation of the orifice that provides different pressure, P_v and different displacement range of the spool valve, x_v. Where, an ideal equation of the orifice can be written as.

$$Q = Kx_v\sqrt{\Delta P_v} \tag{2}$$

By defining the relationship between the volumes in each chamber, the flow rate, and the bulk modulus of the oil, pressure in each chamber can be expressed in equation (3) and (4).

$$P_1 = \frac{\beta}{V_{line} + A_p(x_s + x_p)}\int\left(Q_1 - q_{12} - q_1 - \frac{dV_1}{dt}\right)dt \tag{3}$$

$$P_2 = \frac{\beta}{V_{line} + A_p(x_s - x_p)}\int\left(\frac{dV_2}{dt} - Q_2 - q_{21} - q_2\right)dt \tag{4}$$

The total force produced by the hydraulic actuator through the dynamics equation of spring, damper and moving mass can be represented in equation (5).

$$\begin{aligned} F_p &= A_p(P_1 - P_2) \\ &= M_p\frac{d^2x_p}{dt^2} + B_s\frac{dx_p}{dt} + K_s x_p + F_f \end{aligned} \tag{5}$$

III. SMC with PID Sliding Surface

The implementation of this study will be conducted as demonstrated in the block diagram of Fig. 2. The EHA system will be first formed according to the equation in the modelling Section which parameter will be taken from [16]. Disturbances and uncertainties such as friction and leakage in the EHA system will not taking into consideration.

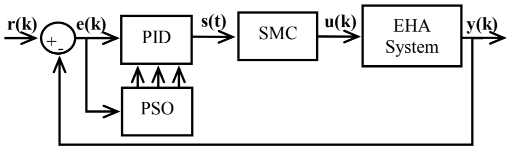

Fig. 2. Block-diagram for the concept of the proposed tuning method.

After the development of EHA system, the conventional PID controller will be then connected to the system plant to control the displacement of the cylinder actuator according to the desired reference input. The variables of K_p, K_i, and K_d will be first obtained through the conventional ZN tuning method. Then the SMC controller will be applied to the system where the PID controller will integrated into the sliding surface of the SMC controller and the observation of the system performances will be done. Lastly, the PSO tuning technique will be used to obtain the variables of the PID sliding surface and compared with the performances of the conventional ZN tuning technique in terms of positioning tracking.

A. Sliding Mode Control Design

SMC controller has been introduced in the early of 60's which fundamental concept is extracted from variable structure control developed in Russia [10]. The most pivotal stage in the establishment of SMC control is the structure of sliding surface which is anticipated to be response to the desired control criterion. The control signal that is reached to the sliding surface is expected to be stay on the surface and slide to the origin point which is the desired position as depicted in Fig. 3.

In general, the sliding surface of SMC control can be formed according to the equation (6).

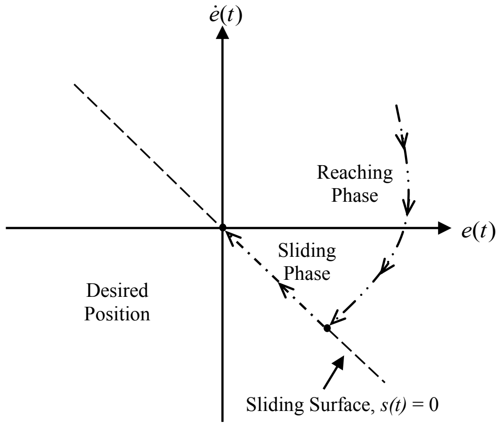

Fig. 3. The structure in the sliding mode control design.

$$s(t) = \left(\lambda + \frac{d}{dt} \right)^{n-1} e(t) \tag{6}$$

where n denotes the system model order to be controlled.

The PID sliding surface for the SMC design implemented into third-order EHA system can be indicated by using the following equation where K_p, K_i, and K_d are referred to the PID parameters [17].

$$s(t) = k_p e(t) + k_i \int_0^t e(\tau) d\tau + k_d \dot{e}(t) \tag{7}$$

The difference between the actual actuator position and the desired trajectory yielding the tracking error as expressed in equation (8).

$$e(t) = x_r(t) - x_p(t) \tag{8}$$

The third derivative of the error which is coming from the third-order model obtained through the linearized EHA system is expressed in the following equation,

$$\dddot{e}(t) = \dddot{x}_r(t) - \dddot{x}_p(t) \tag{9}$$

The general expression of SMC control structure consists of switching control and equivalent control as denoted in equation (10). Where the switching control, u_{sw} corresponding to the reaching phase when $s(t) \neq 0$. While the equivalent control u_{eq} corresponding to the sliding phase when $s(t) = 0$.

$$u_{smc}(t) = u_{eq}(t) + u_{sw}(t) \tag{10}$$

The tracking error will be confined in the sliding surface and converge to the equilibrium point where $s(t) = \dot{s}(t) = \ddot{s}(t) = 0$, where the second derivative of sliding surface is expressed as:

$$\ddot{s}(t) = k_p \ddot{e}(t) + k_i \dot{e}(t) + k_d \dddot{e}(t) \tag{11}$$

Assume that the lumped uncertainty is neglected (L=0), the equivalent control of the SMC control can be defined as

$$u_{eq}(t) = \left(k_d C_n\right)^{-1} \left(k_p \ddot{e}(t) + k_i \dot{e}(t) + \cdots \right.$$
$$\left. \cdots k_d (\dddot{x}_r + A_p \ddot{x}_p + B_p \dot{x}_p)\right) \tag{12}$$

By applying the sign function to the sliding surface, the switching control can be determined as [17]:

$$u_{sw}(t) = \lambda s(t) + k_s sign(\dot{s}(t)) \tag{13}$$

where $\lambda, k_s \in \Re^+$ and $sign(\dot{s}(t))$ is the signum function which has a piecewise function as below:

$$sign(\dot{s}(t)) = \begin{cases} 1 & ; \dot{s}(t) > 0 \\ 0 & ; \dot{s}(t) = 0 \\ -1 & ; \dot{s}(t) < 0 \end{cases} \tag{14}$$

An outstanding stability analysis which is Lyapunov theorem as utilized in [18-20] has been used to verify the stability of the controller through the following Lyapunov function:

$$V(t) = \frac{1}{2} s^2(t) + \frac{1}{2} \dot{s}^2(t) \tag{15}$$

where $V(t) > 0$ and $V(0) = 0$ for $s(t) \neq 0$. The reaching condition as presented in equation (16) is necessary to be followed to ensure the trajectory moving from reaching phase to the sliding phase in the stable condition.

$$\dot{V}(t) = 0, \text{ for } s(t) \neq 0, \dot{s}(t) \neq 0 \tag{16}$$

Substitute (9), (10) and (11) into (16) yielding:

$$\dot{V}(t) = s(t)\dot{s}(t) + \dot{s}(t)\ddot{s}(t)$$
$$= s(t)\dot{s}(t) - k_d C_n \lambda s(t)\dot{s}(t) - k_d C_n k_s |\dot{s}(t)| - k_d L(t)\dot{s}(t) \cdots$$
$$\cdots \leq |\dot{s}(t)| \left[s(t) - k_d C_n \lambda s(t) - k_d C_n k_s - k_d L(t) \right] \cdots$$
$$\cdots \leq |\dot{s}(t)| \left[|s(t)| - k_d C_n \lambda |s(t)| - k_d C_n k_s - k_d L(t) \right] \cdots$$
$$\cdots \leq -|\dot{s}(t)| \left[|s(t)| (k_d C_n \lambda - 1) + k_d C_n k_s - k_d L_{max}(t) \right] \cdots$$
$$\cdots < 0 \tag{17}$$

To guarantee the stability, the requirement of $\lambda > \frac{1}{k_d C_n}$, $k_s > \frac{L_{max}}{C_n}$, and $\dot{V}(t)$ is negative definite for the SMC parameters is necessary to be fulfilled when the system is in reaching phase where, $s(t) \neq 0$ and $\dot{s}(t) \neq 0$.

To ensure the stability of the switching control based on Lyapunov theorem, the chattering effect for the discontinuous function in (13) has been reduced by replace the function of hyperbolic tangent with the boundary layer of φ as proposed in [17].

$$u_{sw}(t) = \lambda s(t) + k_s \tanh\left(\frac{\dot{s}}{\varphi} \right) \tag{18}$$

B. PSO Algorithm

PSO is a popular optimization algorithm, which is a population based optimization tool that applicable to various types of application. The inspiration of the PSO algorithm is came from the swarming behaviour in a flock of birds, a school of fish, or a swarm of bees [21]. In solving the continuous nonlinear problems, this method is found to be outstanding by executing the combination of simplified social and global properties [22].

The XY coordinates within two dimensional searching space will be crossed by each particle or other word known as an agent in the development of PSO technique. The former velocity and position information will be used in the update of the new position of the particles [23]. The best value acquired by each particle will be saved in every iteration. Which will later compare to obtain the personal best values. Between the personal best values, global best value can be computed [22]. Final iteration with the best global best value will be utilized and implemented to the controller of the system.

In the iterations, the particles will change to their new position according to the velocity, v equation in (19), and position, s equation in (20) respectively [23].

$$v_i^{k+1} = wv_i^k + c_1 rand_i x\left(pbest_i - s_i^k\right) + \cdots + c_2 rand_i x\left(gbest_i - s_i^k\right) \quad (19)$$

$$s_i^{k+1} = s_i^k + v_i^{k+1} \quad (20)$$

Fig. 4 demonstrates the concept of alteration in the searching point for the PSO algorithm. Where, s_i^k and s_i^{k+1} are the current and future searching point, v_i^k and v_i^{k+1} denotes the current and future velocity, while the v_{pbest} and v_{gbest} are the velocity based upon personal best and global best respectively. In order to reaching the new point s_i^{k+1}, current velocity v_i^k, local or personal best velocity v_{pbest}, and global best velocity v_{gbest} will be summarized as in equation (19) to obtain the modified velocity v_i^{k+1}.

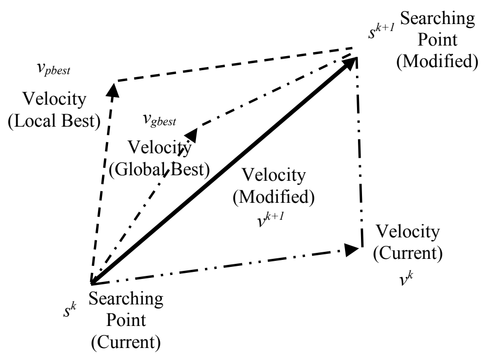

Fig. 4. The changes of searching point for PSO algorithm.

The inertia weight is a crucial factor that controls the impact of each particle in the previous velocity. A small inertia weight favours exploitation while the large inertia weight controls the impact of each particle in the previous velocity. The researcher in [24] implement the inertia weight decreased over time. The purpose in the decline of an inertia weight is to transform the exploratory mode into the exploitative mode. The inertia weight function proposed by [24] to control the convergence of the swarm is expressed in equation (21).

$$w = \left(w_{\max} - \frac{w_{\max} - w_{\min}}{iter_{\max}} \right) x(iter) \quad (21)$$

where, the inertia weight denoted in w, w_{max} is the initial weight coefficient, w_{min} represent the final weight coefficient, the maximum number of iterations represented in $iter_{max}$, and $iter$ represent the current iteration.

IV. Results and Discussion

In the assessment of the position tracking performance for the conventional tuning method and the optimization algorithm employed to the PID sliding surface, the step reference input signal has been fed into the plant and observe the controller tracking ability as shown in Fig. 5. The PID controller parameters obtained through ZN conventional tuning method provide high overshoot and long settling time denoted in cyan dotted output signal. It can be clearly seen through Fig. 5, the overshoot and settling time have been reduced when the SMC controller with PID sliding surface that utilized ZN parameter as its controller parameters denoted in the blue dotted output signal. By utilizing the PSO algorithm, an optimal PID parameters was obtained, which applied to the PID sliding surface and produced the result as represented by the red dotted output signal. The value of k_s = 10 and φ = 15 have been applied in the switching control, and the PID sliding surface parameters obtained through two different tuning methods were tabulated in Table I.

TABLE I. Parameters value of the PID sliding surface

PID	Parameters Values	
	Ziegler-Nichols	PSO Algorithm
Kp	1020	1118.2151
Ki	0.0150	0.0000073
Kd	0.0038	4.0390734

The root mean square error analysis (RMSE) has been utilized to evaluate the error produced by the proposed technique. When the SMC controller applied to the system where the PID controller with ZN parameters, which acting as the sliding surface for the SMC controller, the improvement of 0.0875% has been obtained. Afterward, the PID controller, which variables K_p, K_i, and K_d obtained through PSO tuning technique was applied to the PID sliding surface of the SMC controller and the improvement of 0.6407% has been obtained.

Compared to the PID sliding surface, which variables K_p, K_i, and K_d were obtained through ZN tuning method, 0.5538% improvement has been obtained when the PSO tuning method is applied to the PID sliding surface. The error produced by these tuning technique applied to the conventional PID controller and the PID sliding surface of the SMC controller are tabulated in the Table II.

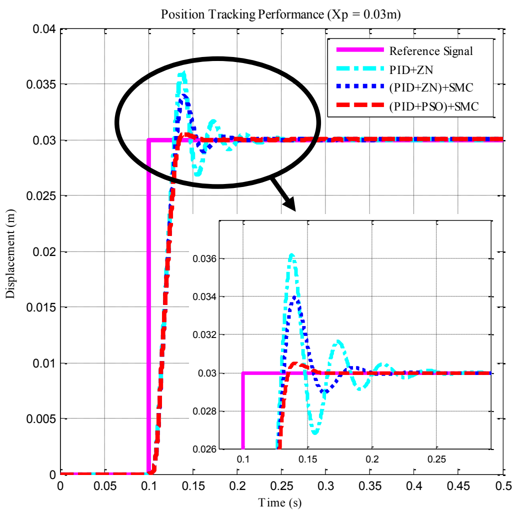

Fig. 5. The output response for step input reference signal.

TABLE II. RMSE FOR THE CONVENTIONAL PID CONTROLLER AND THE PID SLIDING SURFACE OF THE SMC CONTROLLER TUNED USING ZN AND PSO TUNING TECHNIQUE.

Technique	Root Mean Square Error
PID+ZN	0.00524678
(PID+ZN)+SMC	0.00524219
(PID+PSO)+SMC	0.00521316

V. CONCLUSION

In dealing with the system that is highly nonlinear with uncertain behaviour in the real world, controllers that are capable to perform in these circumstances are highly demands. In this paper, the performance of the SMC with the PID sliding surface has been assessed, which taking into account the ZN and the PSO tuning algorithm that implemented in the PID sliding surface. The numerical and simulation results indicated that the SMC is capable to perform better with the PSO variables applied to the sliding surface compare to the conventional ZN variables.

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