OPTIMIZATION OF SLIDING MODE CONTROL PARAMETERS FOR ACCURATE POSITION CONTROL OF LEAD SCREW SYSTEMS USING SERVO MOTORS IN MACHINE TOOLS

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Abstract. In machine tools, position control is a critical factor that directly impacts the accuracy of the machining process. Modern machine tools predominantly utilize electromechanical systems with AC servo motors and lead screws. However, the accuracy of these systems is significantly influenced by the wear and tear of mechanical components, which alters mechanical coefficients over extended periods of operation. To address this issue, this paper employs a sliding mode control algorithm to mitigate the effects of disturbances. Furthermore, a genetic algorithm is incorporated to optimize the sliding mode controller parameters, ensuring robust performance under varying mechanical coefficients. The proposed control structure is validated through numerical simulations in Matlab/Simulink across diverse scenarios, demonstrating its effectiveness in enhancing system performance.
Keywords. Machine tools; Control; Position; Sliding mode; Genetic algorithm.

1 INTRODUCTION

Modern machine tools, such as CNC machines, milling machines, lathes, and cutting machines, are extensively used in machining, particularly in high-precision mechanical manufacturing. Among the various technical challenges in this field, position control stands out as one of the most critical problems to meet precision requirements. Recent research has focused on improving the performance and quality of machine tools, including advancements in mechanical transmission and position control systems.

A typical mechanical transmission system comprises components such as stepper motors, pneumatic cylinders, and lead screws combined with on/off controllers, as implemented in [1]. This approach aims to achieve more precise control over position, speed, and force in industrial equipment. However, the limitation of this system lies in the use of simple controllers for lead screw position control, resulting in suboptimal performance. Similarly, studies [2-3] explored lead screw mechanisms for converting rotational motion into linear motion and proposed identification methods to develop nonlinear dynamic models of these systems, but without addressing control strategies. Research on lead screws in CNC machines, presented in [4-7], primarily focused on analyzing mechanical and electrical energy consumption, emphasizing thermal simulations while neglecting control techniques. Study [8] introduced a method for determining wear in lead screw drives within machine tools, highlighting its impact on precise axis positioning and subsequent control errors. However, the study did not address strategies for maintaining position control accuracy after detecting wear. In another direction, machine learning methods were employed in [9] for monitoring machine tool drives and diagnosing faults in lead screw mechanisms, which improved system performance by addressing issues in the lead screw drive. Additionally, study [10] applied adaptive sliding mode control techniques to CNC machine tools, focusing on force control in grinding machines.

Lead screw drive systems powered by AC servo motors are widely adopted in CNC machines due to their high accuracy and reliable control at both low and high speeds. Control techniques such as fuzzy control, neural networks, and robust control [11-18] have been effectively applied to AC servo systems.

In the aforementioned studies, only study [19], which employs a sliding mode controller combined with an observer, has improved the quality of screw position control in CNC machines with AC servo motor drive systems. However, the controller parameters in [19] were selected merely to satisfy Lyapunov stability conditions, without any optimization process, which may limit the overall control performance. Therefore, in this paper, a Genetic Algorithm (GA) is applied to optimize the parameters of the sliding mode controller with the aim of achieving better position control performance than that reported in [19]. In particular, instead of relying solely on stability-based parameter selection as in [19], the present study performs

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optimization to reduce overshoot, shorten the settling time, and improve the tracking performance under disturbance conditions. Additionally, the proposed analysis is conducted under more rigorous assumptions. GA is an optimization and search algorithm based on the principle of natural selection, simulating the process of biological evolution. It enables the determination of more optimal controller parameters by evaluating factors such as error values, number of generations, and convergence rate. The effectiveness of the proposed method is verified through simulations in Matlab/Simulink under various operating scenarios, and the results are compared with those obtained in [19].
Following this introduction, Section 2 provides a concise presentation of the servo-lead screw system's mathematical model based on [19]. Section 3 details the proposed controller design, while simulation results and discussions are provided in Section 4. Finally, the paper concludes with a summary of findings and implications.

2 MATHEMATICAL MODEL OF THE SERVO – LEAD SCREW SYSTEM

In typical machining systems, such as lathes, milling machines, and drilling machines, AC servo motors are widely used to drive lead screws for precise tool positioning along a single axis. The servo motor generates rotational motion, which is subsequently converted into linear displacement through the lead screw mechanism. The dynamic interaction among the motor, mechanical transmission, and the friction in the screw–nut interface strongly influences the positioning accuracy and response characteristics of the entire drive system. Therefore, both the electrical properties of the servo motor and the mechanical parameters of the lead screw must be considered when formulating the mathematical model and designing the control strategy. These aspects are reflected in the overall control structure shown in Fig. 1 [19], which serves as the foundation for the sliding mode controller developed in the following section.

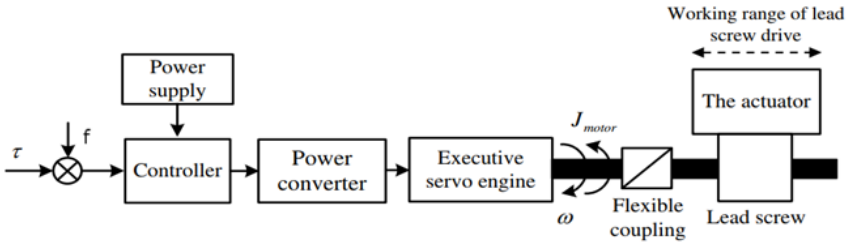


Figure 1: Drive system model [19]

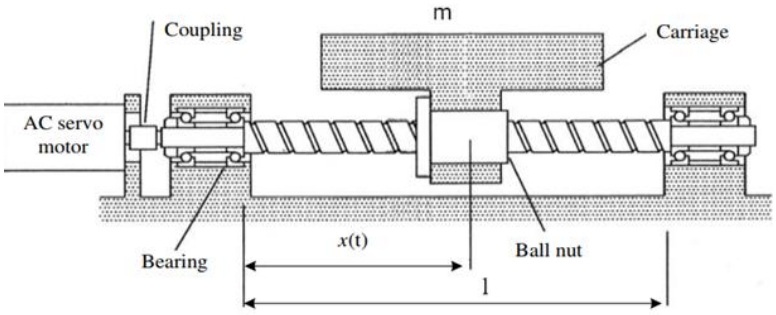


Figure 2: AC servo motors – lead screw drive system [19]

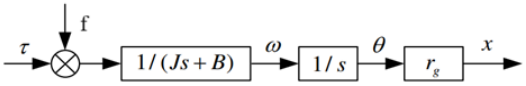


Figure 3: System structure diagram [19]

Considering the system model as shown in Fig. 2, where *l* is the length of the lead screw (in mm), *x(t)* represents the displacement of the tool along the lead screw axis, and *m* is the mass of the tool carriage attached to the lead screw. Additionally, the system includes components such as supports, couplings, mounts, and nuts. Assuming that during operation, the system is influenced by a constant friction coefficient *f(t)* between the lead screw and the nut, the mathematical model of the system is depicted in Fig. 3. In this

model: The input torque is denoted as $\tau(t)$, the motor speed is ω, the motor angular position is θ, the linear position of the lead screw is $x(t)$. According to [19], the motor torque generates rotational motion of the motor shaft, characterized by a moment of inertia J and a viscous friction coefficient B. Let K be the conversion factor from the motor's angular speed to the linear position of the lead screw. The relationship between K and ω can be expressed by the following equation:

$$\omega(t) = \frac{\dot{x}(t)}{K} \tag{1}$$

And according to the structure diagram:

$$\ddot{x}(t) = -\frac{B\dot{x}(t)}{J} + \frac{K\tau(t)}{J} - f(t) \tag{2}$$

Since $f(t)$ is a constant, we have $f(t)=f$; we set $a = \frac{B}{J}; b = \frac{K}{J}; u(t) = \tau(t)$, the equation describing the control system of the lead screw is rewritten as follows:

$$\ddot{x}(t) = -a\dot{x}(t) + bu(t) - f \tag{3}$$

With the input signal as the torque applied to the servo motor shaft $u(t)$, and the output signal as the position of the lead screw shaft $x(t)$, where a, b and f are constants, equation (3) is used to design the sliding mode controller in the next section of the paper.

3 SLIDING MODE CONTROL COMBINE GENETIC ALGORITHM

With $x(t)$ as the output variable, $x_d(t)$ is the input variable (i.e., the desired trajectory). The error between the output value and the desired value is then given by:

$$e(t)=x_d(t)-x(t) \tag{4}$$

The sliding surface is chosen with the sliding variable s, so:

$$s(t) = \dot{e}(t) + de(t) \tag{5}$$

To make the error converge to zero, the coefficient d must be chosen to be positive ($d>0$). Substituting (4) and (5) and differentiating (5), we obtain:

$$\dot{s}(t) = \ddot{e}(t) + d\dot{e}(t) = \ddot{x}_d(t) - \ddot{x}(t) + d\dot{e}(t) = \ddot{x}_d(t) + \dot{a}(t) - bu(t) + f + d\dot{e}(t) \tag{6}$$

We choose the Lyapunov function for equation (6) as follows:

$$V = \frac{1}{2}s^2 \tag{7}$$

Differentiating equation (7) with respect to time, we have:

$$\dot{V} = s\dot{s} = s(\ddot{x}_d + a\dot{x} - bu + f + d\dot{e}) \tag{8}$$

At this point, the control signal can be determined as follows:

$$u(t) = \frac{1}{b}\left[\ddot{x}_d + a\dot{x} + f + d\dot{e} + k\,\mathrm{sgn}(s)\right] \tag{9}$$

To ensure the system is stable, equation (8) must be satisfied $\dot{V} \le 0$, this is proven as follows:

$$\dot{V} = s\dot{s} = s(\ddot{x}_d + a\dot{x} - b\left(\frac{1}{b}\left[\ddot{x}_d + a\dot{x} + f + d\dot{e} + k\,\mathrm{sgn}(s)\right]\right) + f + d\dot{e})$$

$$= s(\ddot{x}_d + a\dot{x} - \ddot{x}_d - a\dot{x} - f - d\dot{e} + -k\,\mathrm{sgn}(s) + f + d\dot{e}) = s(-k\,\mathrm{sgn}(s)) = -k|s| \le 0$$

Thus, with the control signal $u(t)$ in equation (9) determined according to (3), the system is stable according to Lyapunov's stability criterion. Assume b is constant and always positive, the noise f is bounded and defined, and d is always positive.

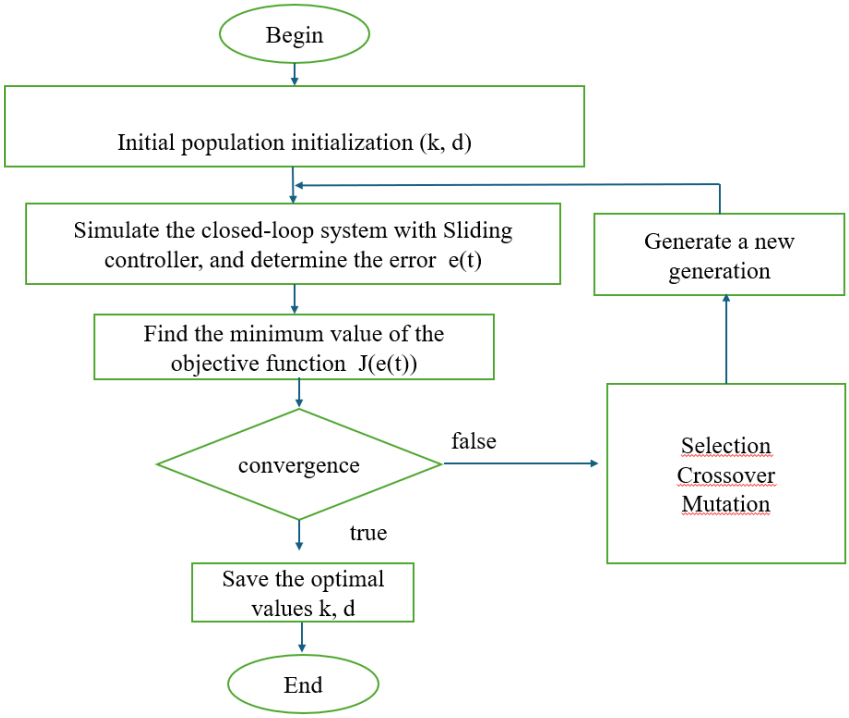


Figure 4: GA Algorithm

To optimize the parameters of the aforementioned sliding mode algorithm, the Genetic Algorithm (GA) is employed. The genetic algorithm applied in this paper is based on [20], with the crossover steps described as the algorithm flowchart in Fig. 4. In this study, the Genetic Algorithm (GA) is employed to optimize the two key parameters of the sliding mode controller, namely the switching gain k and the sliding surface coefficient d. These parameters have a significant influence on the convergence rate and the robustness of the closed-loop system. Instead of selecting k and d based solely on stability considerations, the GA searches for their optimal values by minimizing a performance index that combines overshoot, settling time, and steady-state error. During the optimization process, each candidate solution represents a pair of (k, d), and its fitness is evaluated based on the corresponding control performance obtained from simulation. Through successive generations of selection, crossover, and mutation, the GA iteratively improves the controller parameters and provides an optimal set of values that enhances the tracking performance and robustness of the sliding mode controller.

The objective function is defined based on the tracking error $e(t)$, in which the accumulated squared error over a given simulation interval is considered as the performance index:

$$J = \int_0^T e^2(t)dt \tag{10}$$

By minimizing $J(e(t))$, the GA seeks a pair (k, d) that yields improved tracking accuracy and faster convergence. Each individual in the population represents a candidate solution (k, d) and its fitness is evaluated through the corresponding closed-loop simulation. The main GA parameters used in this study include a population size of 100 individuals and a total of 80 generations. Through iterative selection, crossover, and mutation processes, the algorithm progressively refines the controller parameters and converges toward an optimal configuration that enhances both tracking performance and robustness of the SMC scheme.

The structure of the position control system (Fig. 5) consists of the SMC-GA controller and the plant with the equation (3).

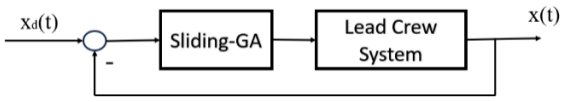


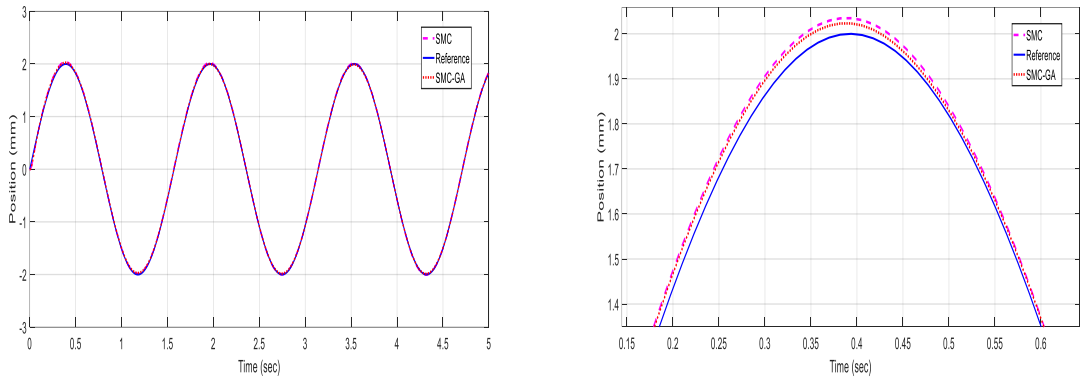
Figure 5: Block diagram of the position control system

4 SIMULATION RESULTS

This section presents the simulation results for the position control system of the lead screw in a machine tool, which uses an AC servo motors. The system is modeled using the parameters from [19], and the controller parameters are detailed in Table 1. The simulation results illustrate the position response of the lead screw, comparing the optimal parameter Sliding mode controller designed with a genetic algorithm (SMC-GA), as proposed in Section 3, against the conventional Sliding mode controller (SMC) based on [19]. The control performance of the SMC-GA relative to the SMC is analyzed under various simulation scenarios, including different setpoint signals and varying disturbance conditions.

Table 1: System and controller parameters

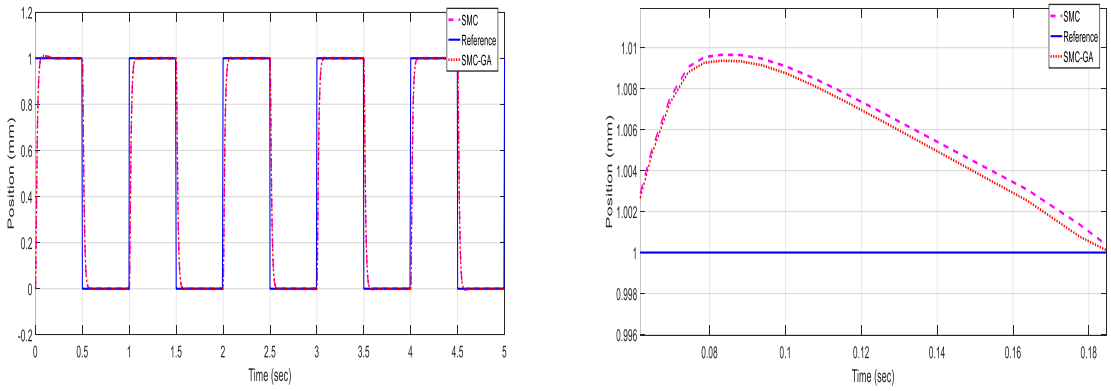
K = 0,05	B = 0,06	L = 0,5
J = 0,03	f = 0,98	a = 2
b = 1,67	d = 25	k = 3



(a) (b)

Figure 6: Position response of the lead screw under a sine wave input signal

Fig. 6, 7, 8, and 9 illustrate the position response of the lead screw corresponding to setpoint signals in the form of a sine wave, square wave, constant value, and varying constant value, respectively. The simulation results demonstrate that both the SMC-GA and SMC controllers exhibit excellent performance. However, the trajectory tracking capability of the SMC-GA controller is superior. The control quality is further analyzed in Table 2, focusing on the scenario where the setpoint signal is constant, as shown in Fig. 8.



(a) (b)

Figure 7: Position response of the lead screw under a pulse input signal

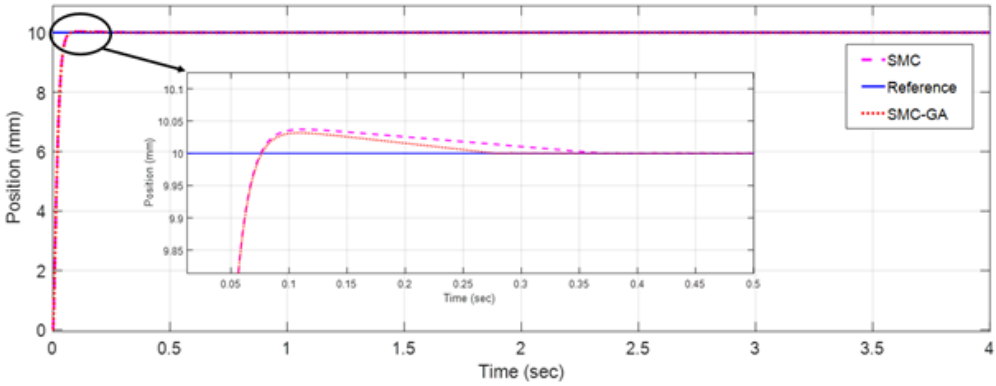


Figure 8: Position response of the lead screw under a constant input signal

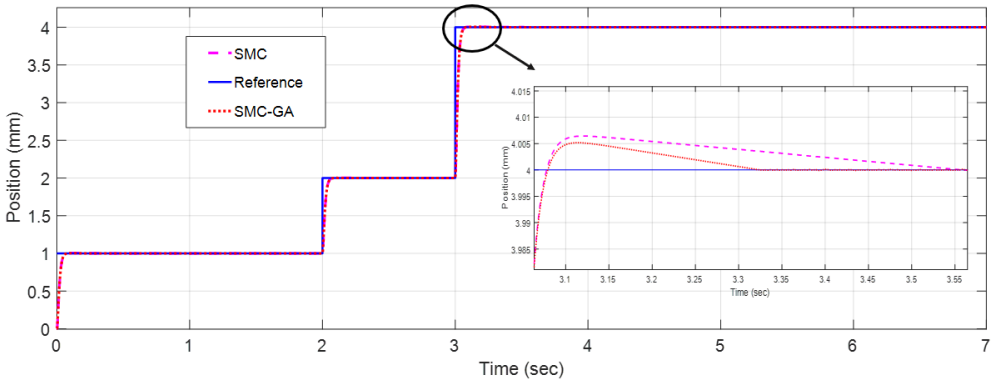


Figure 9: Position response of the lead screw when the setpoint signal is a varying constant

Table 2: Control quality when set constant setpoint signal

Controller	SMC-GA	SMC
Overshoot	0,25%	0,3%
Settling time	0,27s	0,36s
Steady-state error	0	0

To evaluate the performance of the two controllers under noisy conditions, the study assumes the presence of pulse control noise and white noise. The tracking capability of the system is assessed using sine wave and constant input signals, with the corresponding results shown in Fig. 10, 11, 12, and 13.

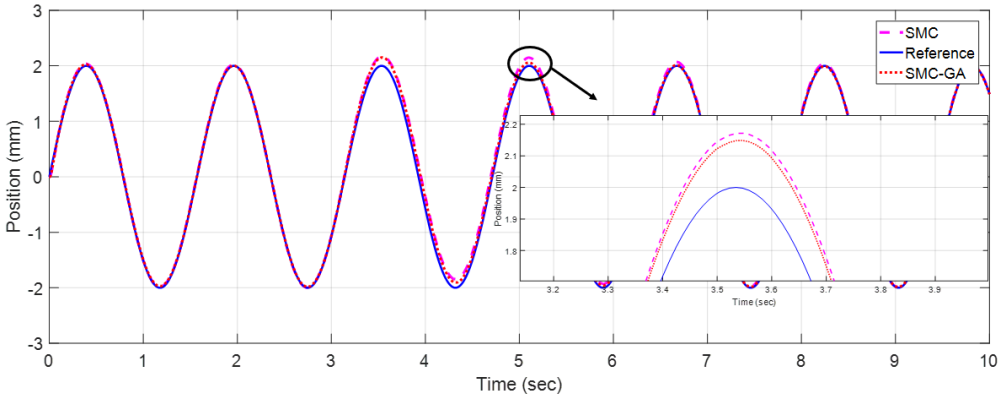


Figure 10: Position response of the lead screw under a sine wave input signal with pulse noise

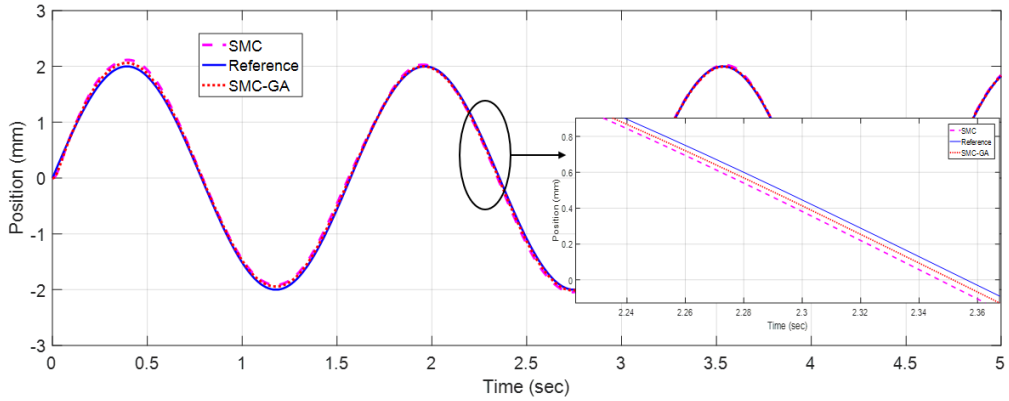


Figure 11: Position response of the lead screw under a sine wave input signal with white noise

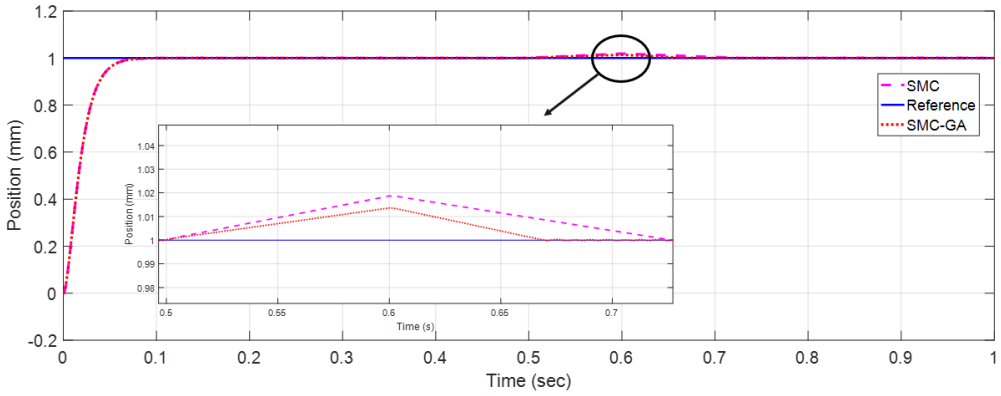


Figure 12: Position response of the lead screw under a constant input signal with pulse noise

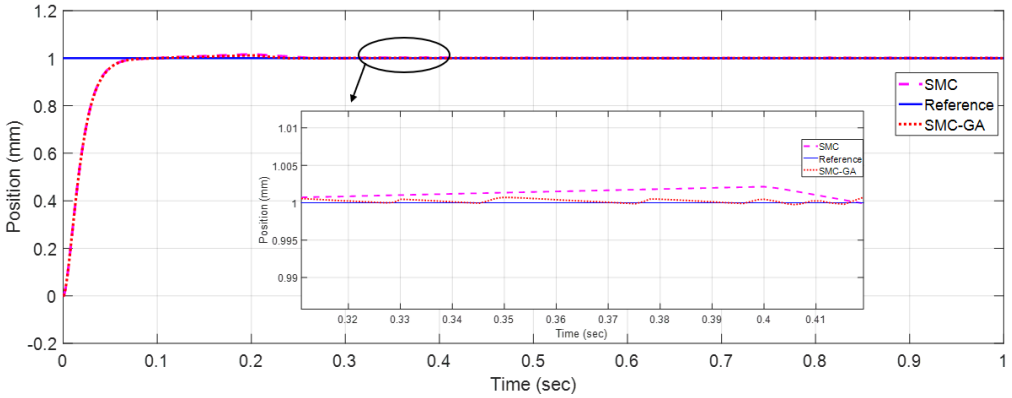


Figure 13: Position response of the lead screw axis with a constant setpoint signal, affected by band limited white noise

The simulation results demonstrate that the performance of the SMC-GA controller is superior to that of the SMC controller. The control quality parameters for the scenario shown in Fig. 13 are provided in Table 3.

Table 3: Control quality when set constant setpoint signal affected by noise

Controller	SMC-GA controller	SMC controller
Overshoot	1,3%	2%
Settling time	0,17s	0,23s
Steady-state error	0	0

Thus, the sliding mode controller with parameters optimized by the genetic algorithm has demonstrated superior tracking performance in this position control problem, compared with the conventional SMC compared to the non-optimized sliding mode controller.

5 CONCLUSIONS

In conclusion, the sliding mode controller with parameters optimized by the genetic algorithm has demonstrated improved tracking performance in the lead-screw position control system for machine tools. The obtained results indicate significant enhancements in accuracy, overshoot reduction, and settling behavior compared with the conventional SMC approach, highlighting the potential applicability of the proposed method in practical machining environments. In conclusion, the sliding mode controller with parameters optimized by the genetic algorithm has demonstrated improved tracking performance in the lead-screw position control system for machine tools. The obtained results indicate significant enhancements in accuracy, overshoot reduction, and settling behavior compared with the conventional SMC approach, highlighting the potential applicability of the proposed method in practical machining environments. Future work will consider practical operating conditions, including friction effects and time-varying system parameters, to further evaluate and extend the robustness of the control strategy.

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TỐI ƯU THAM SỐ BỘ ĐIỀU KHIỂN TRƯỢT ĐIỀU KHIỂN VỊ TRÍ TRỤC VÍT ME TRÊN MÁY CÔNG CỤ SỬ DỤNG ĐỘNG CƠ SERVO

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Tóm tắt. Trong các máy công cụ, điều khiển vị trí là yếu tố then chốt ảnh hưởng trực tiếp đến độ chính xác của quá trình gia công. Các máy công cụ hiện đại chủ yếu sử dụng hệ thống điện cơ kết hợp động cơ servo AC với trục vít me. Tuy nhiên, độ chính xác của hệ thống này bị ảnh hưởng đáng kể bởi sự mài mòn các thành phần cơ khí, dẫn đến sự thay đổi của các thông số cơ học theo thời gian vận hành. Để giải quyết vấn đề này, bài báo áp dụng thuật toán điều khiển trượt nhằm giảm thiểu tác động của nhiễu loạn. Bên cạnh đó, thuật toán di truyền được tích hợp để tối ưu hóa các tham số của bộ điều khiển trượt, đảm bảo khả năng vận hành bền vững ngay cả khi các hệ số cơ học biến đổi. Cấu trúc điều khiển đề xuất đã được kiểm chứng thông qua mô phỏng số trên Matlab/Simulink trong nhiều kịch bản khác nhau, khẳng định rõ hiệu quả trong việc nâng cao chất lượng và hiệu suất của hệ thống.
Từ khóa: Máy công cụ, Điều khiển, Vị trí, Chế độ trượt, Thuật toán di truyền.

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