SUPER TWISTING SLIDING MODE CONTROLLER FOR PRECISE BALL SCREW DRIVEN XY POSITIONING MILLING TABLE

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ABSTRACT: Servo drive system in positioning control requires precision, stability, and robustness against system non-linearity, un-modeled system dynamics, and input disturbance. A robust controller in a servo motor control system will realised these requirements. The objective of the work presented in this paper was to design and evaluate the performances of a Super Twisting Sliding Mode Controller (ST-SMC) for control of a ball screw driven milling table under the influence of input force disturbance. The ST-SMC control law design parameters; λ, L and W were selected using the heuristics method. The controller performances were analysed numerically using MATLAB and Simulink software based on the magnitude of the root mean square (RMSE) of the tracking errors. Reference signals with amplitude of 1 mm, 2 mm, and 3 mm at frequency of 2 Hz were selected as input signal with a random filtered white noise as the input disturbance. In case of the x-axis, results showed the precision of ST-SMC with near zero RMSE values of 0.0012 mm, 0.0093 mm, and 0.0259 mm respectively. For disturbance rejection, the percentage variation in RMSE values for cases with and without the input noise ranged from 1.5% to 29.2% compared to 15% to 42% in the case of cascade P/PI controller. The performance of the ST-SMC is to be further extended for multiple types input disturbance rejection.

KEYWORDS: *Robust Control, Super Twisting Sliding Mode Controller (ST-SMC), Precision, Positioning Table, Disturbance*

1.0 INTRODUCTION

The success of machining process by machine tools or any mechatronics products depends on the level of accuracy and precision offered by the many different technologies that contribute in the design, development, and application of the system. There exist different control strategies, including linear and nonlinear control methods to address issues related to precision and accuracy of motion in mechatronic system. In recent years, nonlinear robust controllers' development and applications have attracted the attention of many researchers due to their ability to address the various requirements put forward by nonlinear systems. Among them, N-PID controller offers significant advantage over classical Proportional-Integral-Derivative (PID) controllers – a type of controller that is known for its simple structure and functions that are based on the proportional, integral and derivative of the error signals. The addition of a nonlinear gain in the control structure of the conventional PID controller has enabled handling of the system nonlinearity as mentioned by [1].

Nonlinear robust controllers, such as the traditional sliding mode controller [2] (SMC) and many of its variants [3-6] have become attractive solutions to meet the complex demands that classical controllers such as PID controllers and cascade controllers [7] are no longer able to meet. SMC-based controllers are known for their robustness against input disturbance thus preserving high control performances. In machining, precision of the parts produced is adversely affected by chattering-induced machine vibration originating mostly as the effect of the cutting forces that acted on the machine servo systems. Higher order sliding mode controller (HOSMC), first introduced by Levant [8] offers an attractive solution to compensate against the input disturbance force. HOSMC includes Twisting and Super Twisting Sliding Mode Control [9-12]. These control approaches provided almost chattering-free performance while maintaining a high level of disturbance rejection property [13-14].

In literature, due to its superiority, Super Twisting Sliding Mode Controller (ST-SMC) and many of its variants have been designed and applied. However, very limited works have been presented on design and analysis of ST-SMC in machining environment especially with regards to the controller ability to reject direct input of force disturbance into the controller's structure. Also, this work analysed the contour-following ability of the controller in coupled mechanism such as an XY positioning table driven by ball screw mechanism. The performances of the controller were analysed with respect to input disturbance and chattering effect. The effectiveness of ST-SMC was benchmarked against the classical cascade P/PI controller.

This paper is organized as follows. Section 2 describes the research methodology that includes the experimental system setup and the controller design methodology. The following section 3 presents the results and subsequent discussion. Finally, section 4 concludes the findings with statements on future recommendations.

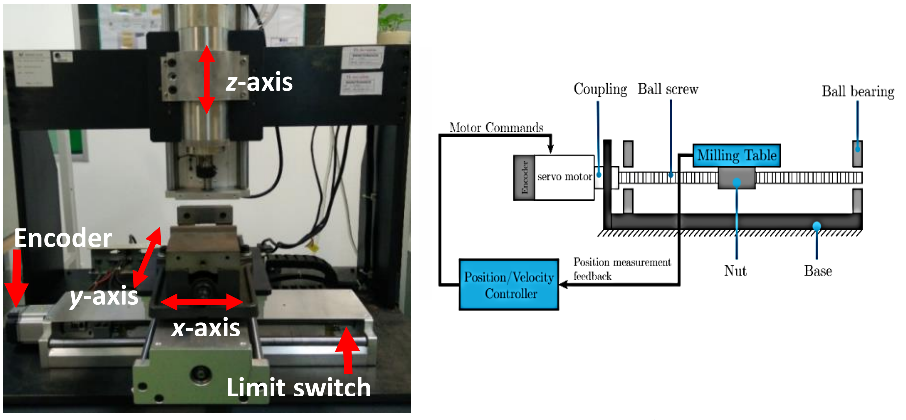
2.0 METHODOLOGY

2.1 System Setup and Identification

The ST-SMC controller was applied to an XY milling table positioning system driven by ball-screw mechanism in all of its three axes. Figure 1 (a) and 1 (b) show the system and the corresponding structure. A Panasonic MSMD 022GIU A.C. servo motor is equipped on each axis and was coupled to the ball screw drive mechanism with a bracket and guided by a sliding rod mechanism. The XY positioning table has a dimension of 630 mm (length) x 470 mm (width) x 815 mm (height) and weight around 100 kg. Each axis has a maximum effective travel distance of 300 mm. Both x and y axes are equipped with incremental encoders for position measurement with a resolution of 0.0005 mm/pulse. Three limit switches were attached near the end of each axis to avoid over travelled.

A frequency domain identification method [15-16] was applied to retrieve the system transfer function. The single-input-single-output (SISO) linear time-invariant parametric model with time delay, τ_d is described in Equation (1) and listed in Table 1. The transfer function describes the dynamic relation between the input voltage to the drive system, $u(t)$ and the output position, $y(t)$:

$$\frac{Y(s)}{U(s)} = \frac{A}{s(s+B)+C}e^{-\tau_d s} \quad (1)$$



(a) (b)

Figure 1: (a) XY positioning milling table ball screw-driven system by Googol Tech Series (b) Structure of the ball screw-driven system

Table 1: System parameters

Axis	*A*	*B*	*C*	τ_d
x	78020	163	193.3	0.0012 s
y	69380	144	166	0.0013 s

2.2 Controller Design – Super Twisting Sliding Mode Control

Super twisting sliding mode control (ST-SMC) structure consists of two main components; namely the control law and the switching function. Figure 2 illustrates the overall structure of the controller that consists of a switching function, the equivalent control (the control law), and estimator for speed signal derivation.

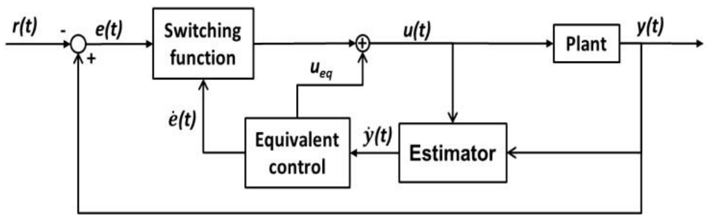


Figure 2: ST-SMC basic controller scheme

2.2.1 Switching Function

Switching function, $s(t)$ is also known as sliding surface. It is a geometrical locus with boundaries where desired response is exhibited when the system is on the surface [2]. It is a function that relates tracking error, $e(t)$ and the first-time derivative of tracking error, $\dot{e}(t)$. Switching function is represented by the following Equation (2) and Equation (3):

$$s(t)=\left(\lambda+\frac{d}{dt}\right)^{n-1}\cdot e(t) \tag{2}$$

$$e(t) = y(t) - r(t) \tag{3}$$

Where, λ is a positive constant while n represents the order of the uncontrolled system. The desired input position and the actual output position are represented by $r(t)$ and $y(t)$ respectively. Equation (2) and Equation (3) were extended further to generate the first derivative of the sliding surface, and the second derivative of the tracking error. These are shown in Equation (4) and Equation (5). Equation (6) that describes the derivative of the sliding surface is extended further using Equation (1) and Equation (5) resulting in Equation (6) a final representation of the sliding surface.

$$\dot{s}(t) = \lambda\dot{e}(t) + \ddot{e}(t) \tag{4}$$

$$\ddot{e}(t) = \ddot{y}(t) - \ddot{r}(t) \tag{5}$$

$$\dot{s}(t) = \lambda\dot{e}(t) + Au(t) - Cy(t) - By(t) - \ddot{r}(t) \tag{6}$$

2.2.2 Control Laws

The control law of ST-SMC comprises three components, namely; the equivalent control, $u_{eq}(t)$, a continuous state function, and the discontinuous input with integrator, $u_1(t)$: Equivalent control, $u_{eq}(t)$ is derived from Equation (6) at the time of sliding that is when both $s(t) = 0$ and $\dot{s}(t) = 0$. Thus,

$$u_{eq}(t) = \frac{1}{A}(Cy(t) + B\dot{y}(t) + \ddot{r}(t) - \lambda\dot{e}(t)), \tag{7}$$

$$u(t) = u_{eq}(t) - L\left|s(t)\right|^{0.5} sign\,(s(t)) + u_1(t), \tag{8}$$

$$\dot{u}_1(t) = -W \cdot sign\,(s(t)), \tag{9}$$

where λ, L, and W are positive gains. Equation (8) and (9) are shown as the control laws of ST-SMC. The updated derivative of the sliding function is then,

$$\dot{s}(t) = -L\left|s(t)\right|^{0.5} sign\,(s(t)) - W\int sign\,(s(t)). \tag{10}$$

2.2.3 Design and Analysis of ST-SMC Control Parameters

The ST-SMC parameters, namely the constants λ, L, and W were selected based on heuristics analysis performed with the objective to reach minimum position tracking errors indicated by the values of the root mean square of the errors (RMSE). Simulations were performed on the controller scheme with input reference amplitude of 1 mm and 2 Hz frequency. Table 2 lists the results of the analysis for both axes whereby the influences of each parameter on the magnitude of the position tracking errors were evaluated.

Table 2: Summary of ST-SMC design parameter analysis for *X*-axis

Axis	λ(mm)	*W*	*L*	RMSE (mm)
x-axis	60	0.1900	0.0350	0.1520
	100	0.2150	0.0250	0.0428
	200	0.1250	0.0017	0.0175
	350	0.2150	0.0150	0.0215
y-axis	50	0.0700	0.0114	0.0158
	80	0.0900	0.0250	0.0108
	110	0.1000	0.0250	0.0104
	200	0.0900	0.0100	0.0102

General observation of Table 1 showed that increasing λ, *L*, and *W* have resulted in reduced position error as observed by the RMSE values. ST-SMC design parameters consisting of λ, *L*, and *W* values of 800, 0.6, and 0.006 were selected striking a balance between system performance that is least magnitude of position errors and ensuring system stability in term of quality of the control command signal, $u(t)$.

3.0 RESULTS AND DISCUSSION

The performance of the ST-SMC was analyzed using MATLAB and Simulink software and evaluated based on the magnitude of the RMSE tracking error with and without input force disturbance. Input disturbance was inserted to evaluate the controller robustness against input force. The ST-SMC controllers were applied on each axis of the XY positioning table as illustrated for the case of x-axis in Figure 3.

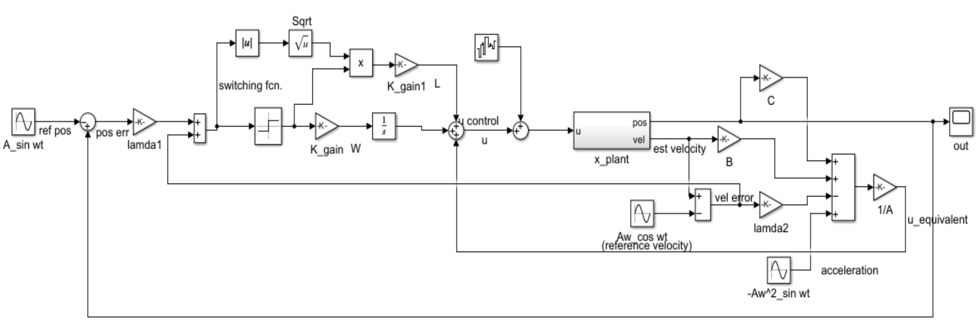


Figure 3: ST-SMC implementation for x-axis

The controller performances were evaluated for reference input of 1, 2, and 3 mm at 2 Hz frequency. Table 3 lists tracking performance results of each axis in the case of with and without input disturbance. Here, random white noise signal of amplitudes 0.04 and 0.02 volts were applied as the input disturbances. Tracking performances were evaluated using the RMSE values that captured the average tracking errors over a period of time. In both axes, as with linear system, the magnitude of tracking errors increased with increased in reference amplitude. However, less variations in the RMSE values were recorded as the amplitude of the reference signal increased. For example, in case of the x-axis, the percentage in variation was reduced from 29.2% to 1.5%. This was due to the fact that the noise disturbance signal remained constant at higher reference magnitude. The small percentage variation confirmed the effectiveness of the controller in rejecting the influence of the input force. Figure 4 illustrates the effect of disturbance on input reference signal which then translated into position errors.

Table 3: Results of controller performances for x-axis and y-axis.

Axis	Amplitude (mm)	Noise (mm)	RMSE (mm)		
			without dist.	with dist.	Variations (%)
x-axis	1	0.04	0.0012	0.0362	29.2 %
	2		0.0093	0.0621	5.7 %
	3		0.0259	0.0658	1.5 %
y-axis	1	0.02	0.0033	0.0764	22.2 %
	2		0.0187	0.0949	4.1 %
	3		0.0492	0.1180	1.4 %

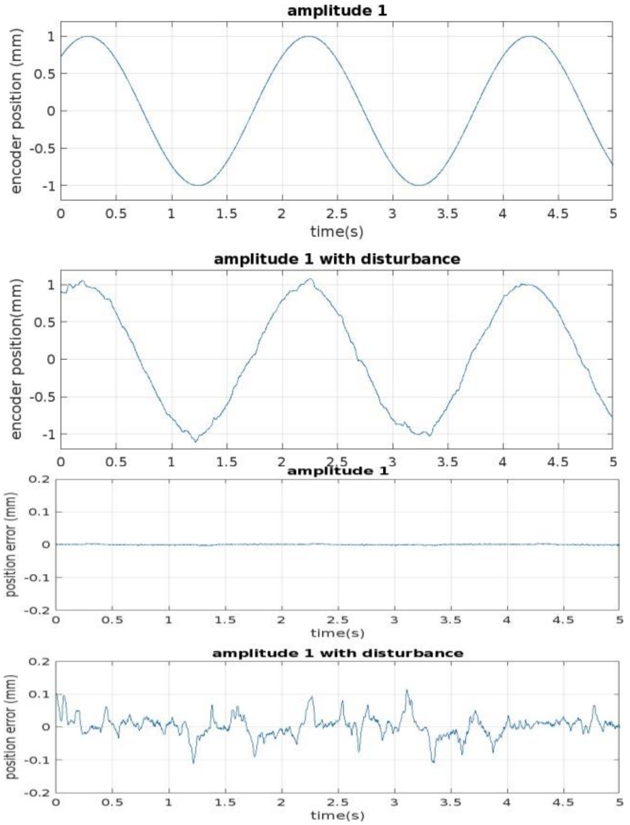


Figure 4: Encoder position and position error for x-axis

In the second analysis, both the x and y axes were activated to evaluate the controller contour tracking performance. Table 4 summarizes the results of the contour tracking performance with RMSE values for each axis. Similar observations were recorded as in the case of individual axis excitation. The variation difference was actually improved over previous individual result as in the example of 1 mm amplitude and 2 Hz frequency whereby the % variation dropped from a maximum of 29% to only 13.4%.

Table 4: Results of controller performances for circular motion

Axis	Amplitude (mm)	Noise		RMSE		
		x-axis	y-axis	without disturbance.	with disturbance	variations (%)
XY	1	0.04	0.02	0.0035	0.0503	13.4 %
	2			0.0180	0.0712	3.0 %
	3			0.0430	0.0994	1.3 %

Figure 5 illustrates contour tracking results for the case of 1 mm and 2 Hz input reference with disturbance.

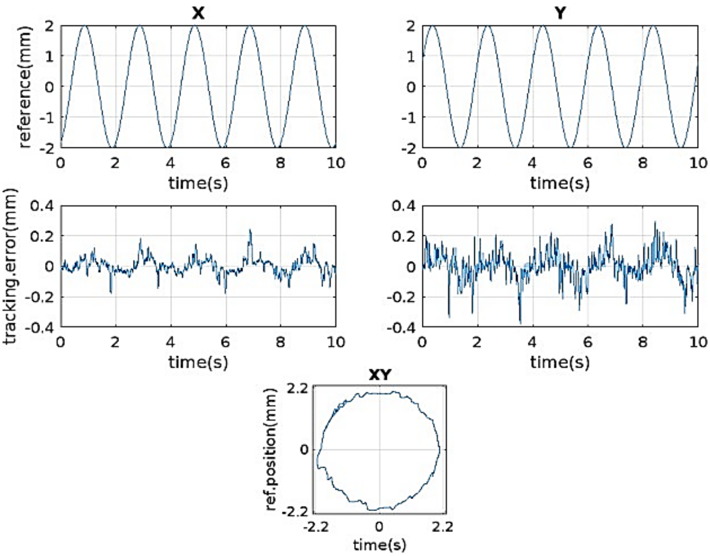


Figure 5: Contour tracking errors for 1 mm and 2 Hz input reference

The performances of the ST-SMC controller were compared against cascade P/PI controller [7], a common classical controller widely applied for control of industrial machine. Table 5 lists results of the cascade P/PI tracking performances at similar input reference and input disturbance. Results showed that the variation in performances with respect to the effect of the input disturbance were larger than that recorded for ST-SMC. Here, the percentages in variation recorded were 52% to 14% in the case of x-axis in comparison to 29.2% to 1.5% in the case of ST-SMC for similar input reference signal amplitudes and frequencies as tabulated in Table 3. This shows the advantages and strength of ST-SMC in rejecting input disturbance for position control of x and y axes in a system utilizing ball and screw mechanism.

Table 5: Results of controller performances for x-axis and y-axis using cascade P/PI controller

Axis	Amplitude (mm)	Noise (mm)	RMSE (mm)		
			without dist.	with dist.	Variations (%)
x -axis	1	0.04	0.0027	0.0167	52.0 %
	2		0.0051	0.0174	24.0 %
	3		0.0076	0.0184	14.0 %
y-axis	1	0.02	0.0026	0.0150	48.0 %
	2		0.0051	0.0168	23.0 %
	3		0.0076	0.0185	14.0 %

4.0 CONCLUSION

This paper presented work on design, analysis, and development of an ST-SMC position control for x and y axes of a CNC ball and screw driven mechanism milling table. The ST-SMC controller parameters (λ, L, and W) were first designed and analysed for optimal performance using the heuristic method. The performances of the controller were evaluated according to the RMSE values of the tracking position errors of both axes. In addition to tracking performance, the ability of the controller to reject input disturbance force is also essential especially in milling process whereby the drives system was continuously being subjected to input cutting force. Therefore, a position controller that is robust against input force disturbance is desired. The ST-SMC position controller had successfully rejected white noise input disturbance force with better efficiency compared to the standard and a more common type of controller that was the cascade P/PI. In future studies, a more versatile and robust ST-SMC can be developed by addition of add-on module to the control structure with dedicated and specific function to further enhance the controller performance against input forces such the cutting force and friction force.

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AUTHOR CONTRIBUTIONS

M. Maharof: Conceptualization, Methodology, Software, Writing-Original Draft Preparation; Z. Jamaludin: Data Curation, Validation, Supervision; S. Mohammad: Software, Validation; A. Rashid: Writing-Reviewing; S. Ahmed: Data Curation, Validation; L. Abdullah: Writing-Reviewing and Editing

CONFLICTS OF INTEREST

The manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agree with its submission and declare no conflict of interest on the manuscript.

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