Emerging Technologies and Engineering Journal

EngiScience Publisher

Research Article

Simplified Sliding Mode Control of a Single-Link Planar Robot

Muhammad Usman Ilyasu [1], Mohammed Ahmed [2,*], Salihu Abdulmumini Jalo [3], Abdulqadiri Bello Abdulqadiri [4], Babul Salam Kader Ibrahim [5], Balkisu Umar Bapetel [3]

[1] Department of Electrical and Electronics Engineering, School of Engineering and Engineering Technology, Federal Polytechnic, Bali, 672102, Nigeria

[2] Department of Electrical and Electronics Engineering, Faculty of Engineering and Engineering Technology, Abubakar Tafawa Balewa University, Bauchi, 740272, Nigeria

[3] Department of Electrical and Electronics Engineering, School of Engineering Technology, Adamawa State Polytechnic, Yola, 640101, Nigeria

[4] Department of Electrical & Electronics Engineering, Faculty of Engineering, Nile University of Nigeria, Abuja, 900001, Nigeria

[5] GUST Engineering and Applied Innovation Research Centre (GEAR), Gulf University for Science and Technology, Hawally, 32093, Kuwait

*Corresponding Author: Mohammed Ahmed, E-mail: inunugoloma@yahoo.com

Article Info

Article History

Received Jan 15, 2025

Revised Feb 07, 2026

Accepted Feb 25, 2026

Keywords

Single-Link Planar Robot

Control systems

Proportional Derivative Control

Sliding Mode Control

Abstract

Robotic technologies are becoming more advanced and are becoming more popular. Requirements are high levels of accuracy and operational speed, such as in surgery and manufacturing. These targets were highly challenging and could be enhanced by employing suitable control systems. Nonlinear control schemes were characterised by high accuracy and robustness, but by high computational time. Hence, the study simplified the Sliding Mode Control (SMC) scheme for a single link planar robot and was referred to as the Simplified Sliding Mode Control (RSMC), which was compared with the normal version referred to as Normal Sliding Mode Control (NSMC) and the gain scheduling based Proportional Derivative Control (GPDC). The effect considered was friction, and it was limited to simulation studies conducted using the SIMULINK/MATLAB software. Results showed that the proposed controller, RSMC, has an algorithm length that is at least 50% shorter than that of the NSMC, with a simplicity similar to that of the GPDC. Results also indicated achieving a settling time of 1.5s, a rise time of 0.8s, 0% overshoot, and a cumulative error of about 250, maintaining the same results with disturbance. The system with the NSMC showed the corresponding parameters as 2.0s, 1.8s, 0% and 260, respectively, without disturbance, and as 3s, 3s, 0% and 310, respectively, with disturbance. It therefore implied that a shorter RSMC algorithm means lower execution time. The RSMC showed superior performance, indicating higher accuracy, operational speed and robustness.

1. Introduction

The application of robotics is continuously becoming popular, especially in areas where accuracy and speed are highly required, such as surgery [1-5] and manufacturing [6, 7]. Combined precision and speed, as the principal targets, are challenging due to the nature of the robotic systems and the complexity of the tasks to be carried out. Hence, the accuracy in achieving such operations is regarded as highly important and can, however, be enhanced by employing suitable control systems.

The Model Predictive Control (MPC) was investigated against the Proportional Integral Derivative (PID), the Linear Quadratic Regulator (LQR) and Full State Feedback (FSB). The MPC outperformed the rest [8]. In another development, the PID and LQR were studied, and, according to the authors, improvements were observed [9]. The authors proposed the Adaptive MPC (AMPC) to maintain the performance achievable with the nonlinear MPC. In addition, the computational complexity was reduced compared to the linear MPC (LMPC) version [10]. The LQR and pole placement were explored by [11]. The authors claimed that vibrations were suppressed and stability was enhanced. A two-layered 'Adaptive Super-Twisting Sliding Mode Control (ASTSMC)' approach was presented by [12] for controlling the link position. A nonlinear model of the system was utilised, and the results were compared with those of PID and SMC. The proposed technique outperformed the two. Two enhanced versions of the 'Terminal Sliding Mode Control (TSMC)' approach were proposed, and the results showed better tracking performance [13]. The indication was that the nonlinear control approaches, including SMC, showed superior results compared to others. The shortcomings of linear schemes might be due to the nonlinearity of real systems, which are difficult to approximate, making compensation very difficult.

Nonlinear control methods are highly accurate and robust, and the SMC belongs to this class [12-16], though they are characterised by high computational time [17, 18]. Therefore, the study focuses on simplifying the sliding mode control (SMC) scheme for a single-link planar robot. In this way, the desirable properties of the SMC are retained, and it then acquires the simplicity of linear schemes, especially the PID.

2. Methods

The simplified system block diagram is shown in Figure 1. The desired position is the reference position of the robotic link, and the actual position or response gives the exact position of the link. The sensor is connected to the response and provides a suitable link back to the reference. Part of the controller's function is to compare the intended desired position of the link with its actual position and produce an error. The controller uses the amount of error to decide the amount of compensation to apply. The controller generates the actuating signal u, which is sometimes referred to as the control signal, and it is used to actuate or drive the plant, which is the link of the planar robot in the study.

The research was conducted using an analytical model of the single-link planar robot. A constant-rate-reaching law-based sliding mode controller was explored in the study. It was simplified by shortening the algorithm to reduce the computational burden. The control scheme realised was referred to as the simplified sliding mode control (RSMC), which was compared with the normal version (NSMC) and the gain-scheduling based proportional-derivative control (GPDC). The disturbance considered was Coulomb friction, capable of inducing an error of about 10^0. The simulation studies were executed employing the SIMULINK/MATLAB software.

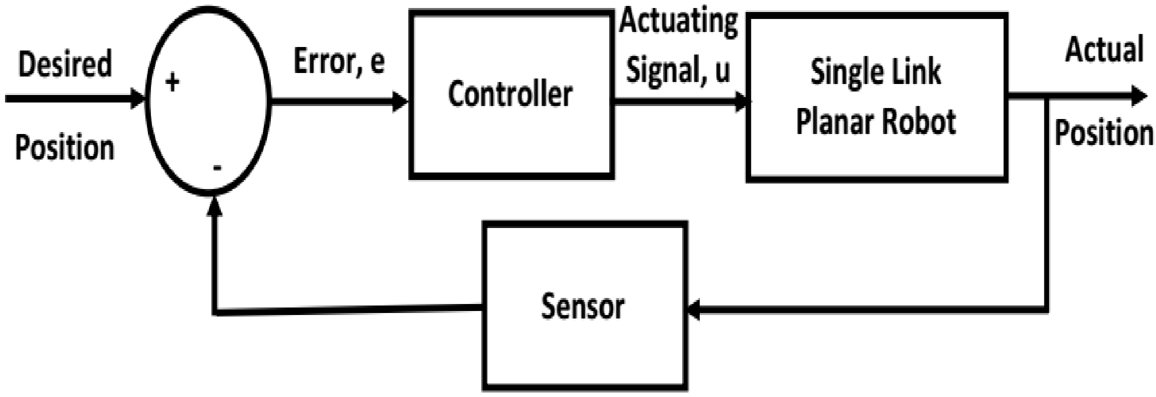

Figure 1. The block diagram of the single-link planar robot system.

The single-link planar robot model was adapted from the works of Philips *et al.* [19] as given by equation (1) and the parameters K_1, K_2, N and τ, where: 10 (constant, K_1), 100 (constant, K_2), 1/100 (turns ratio, N) and 0.2 s (time constant, τ) respectively. The servomotor voltage driving the robotic link was limited to 24 V.

$$\frac{U_R(s)}{\theta_R(s)} = \frac{K_1 K_2 N}{s(\tau s+1)} \tag{1}$$

The control law of the GPDC was given by equation (2) with K_P and K_D given by 3.5 and 2, respectively.

$$U_{GPDC}(s) = K_P E(s) + K_D s E(s) \tag{2}$$

The RSMC control law was obtained using the constant-rate reaching law [20], with an additional modification similar to that of the PD controller. It was also realised to be similar to that of the GPDC, as shown by (3) and (4). Equation (3) was the surface, and the parameters c, σ and K_R were 2, 1 and 2, respectively.

$$s(t) = ce(t) + \dot{e}(t) \tag{3}$$

$$U_{RSMC}(s) = K_R E(s) + sE(s) + \sigma Sgn\ (s) \tag{4}$$

The control law with the NSMC was as given by equations (5) - (8). The values remained as mentioned above. Equation (5) is the sliding surface, and (6) is its derivative. Equation (7) showed that the constant-rate reaching law was chosen. Equation (8) is obtained by converting equation (1) to a differential equation, substituting the relevant values of the terms, and then substituting (7) and (8) into (6). Finally, making U the subject gives the control law.

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

$$\dot{s}(t) = c\dot{e}(t) + \ddot{e}(t) \tag{6}$$

$$\dot{s}(t) = -\sigma Sgn(s) \tag{7}$$

$$4U(s) = 2\theta_R(s) - C\dot{E}(s) - \sigma Sgn(s) \tag{8}$$

$$U_{NSMC}(s) = 0.5\theta_R(s) + 0.25C\dot{E}(s) + \ddot{\theta}_D(s) + 0.25\sigma Sgn\,(s) \tag{9}$$

3. Results and Discussions

The outcome starts with a simple discussion of the lengths of the control algorithms, which could aid in giving a clear picture of the burden of how the computer executes them. Considering the lengths of the control algorithms using the RSMC and the NSMC, it was observed that the RSMC was realised with steps described by equations (3) and (4), with four multiplications between the different parameters together with three addition operations. In the case of the NSMC, there were four steps, as described by equations (5)-(9), eleven multiplications of different parameters, and about seven additions of the parameters. Hence, the length of the control algorithm realised using the RSMC scheme was observed to be shorter than that of the NSMC; the steps were reduced to two, which were four with the NSMC, multiplications were four with the RSMC, compared to eleven with the NSMC, and additions were four with the RSMC, while they were seven with the NSMC. It therefore implied reducing the execution time by more than 50% with the RSMC compared to the NSMC technique. Meaning that it was reduced stepwise, lessening execution time and hence simplifying. Therefore, the reduction in the execution time implied a lower computational burden.

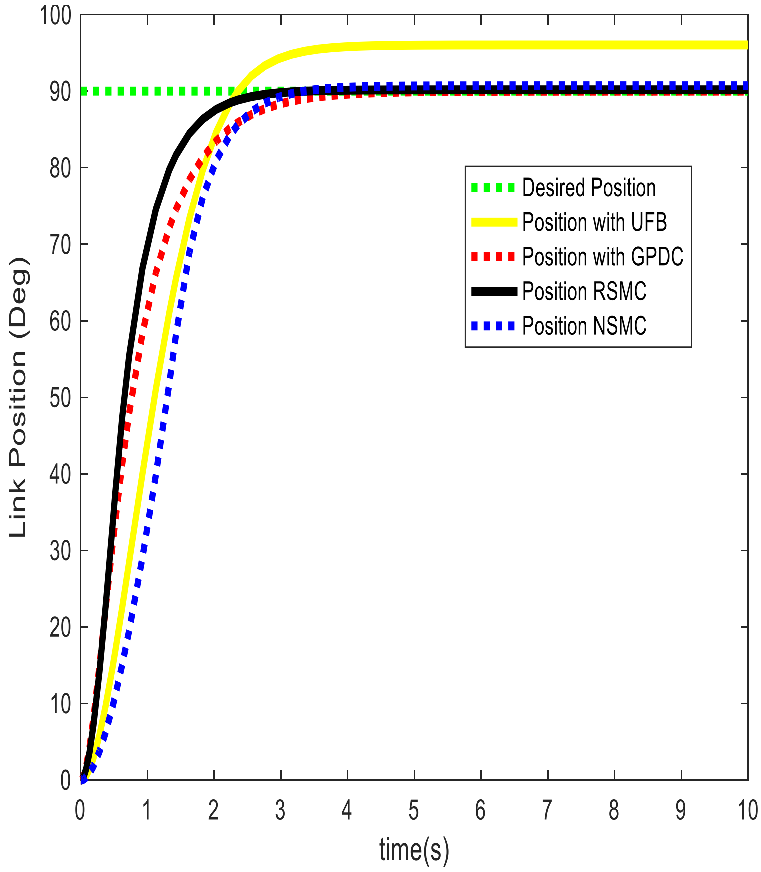

Figure 2. Step response without considering disturbance.

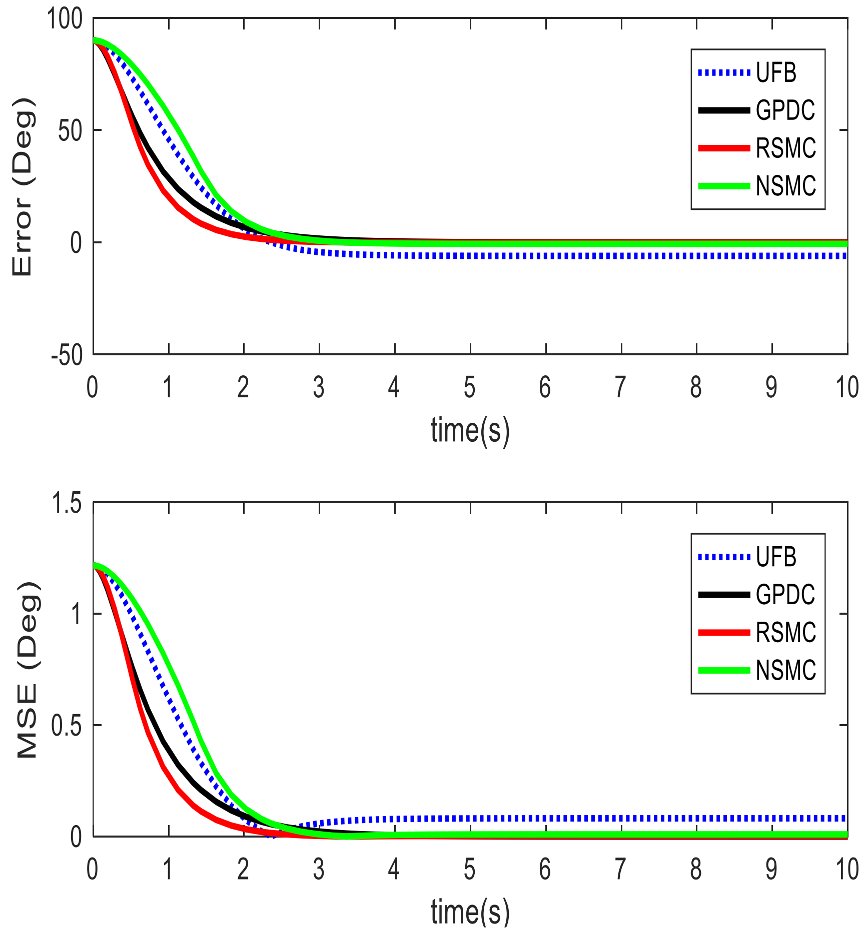

Figure 3. Error graphs without considering disturbance.

Table 1. No disturbance results.

Parameter	Control Method			
	UFB	**GPDC**	**RSMC**	**NSMC**
Settling time (s)	3.5	2.5	1.5	2.0
Steady State error (^{0})	6^0	0^0	0^0	0^0
Rise time (s)	1.8	1.8	0.5	1.8
Overshoot (%)	9	0	0	0
Peak time (s)	3	3	2	2

The system's tracking response without any disturbance is shown in Figure 2 and Table 1. Figure 3 portrayed the levels of errors during the evaluation. The cumulative errors for the different schemes were obtained as follows: 320 with the UFB, 220 with the GPDC, 140 with the RSMC, and 210 with the NSMC, as indicated by the summation of the errors shown in Figure 3. All these showed that the systems with the RSMC and NSMC are almost identical and better than the GPDC, with lower tracking errors. The system with the Unity Feedback (UFB) or without a controller indicated that it would be difficult to compensate for errors (resulting in steady-state errors). As observed, it maintained a steady-state error of about 60, as shown in Figure 2.

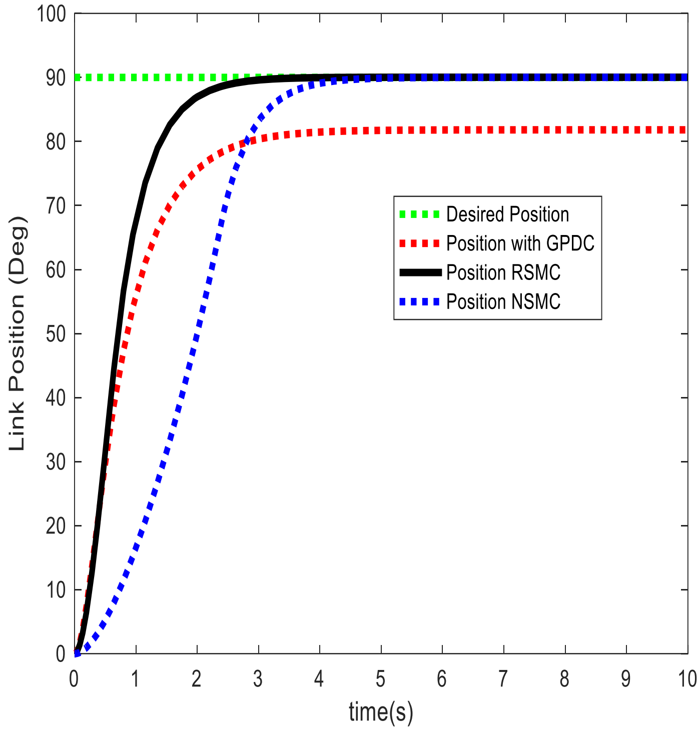

Figure 4. Step response considering disturbance.

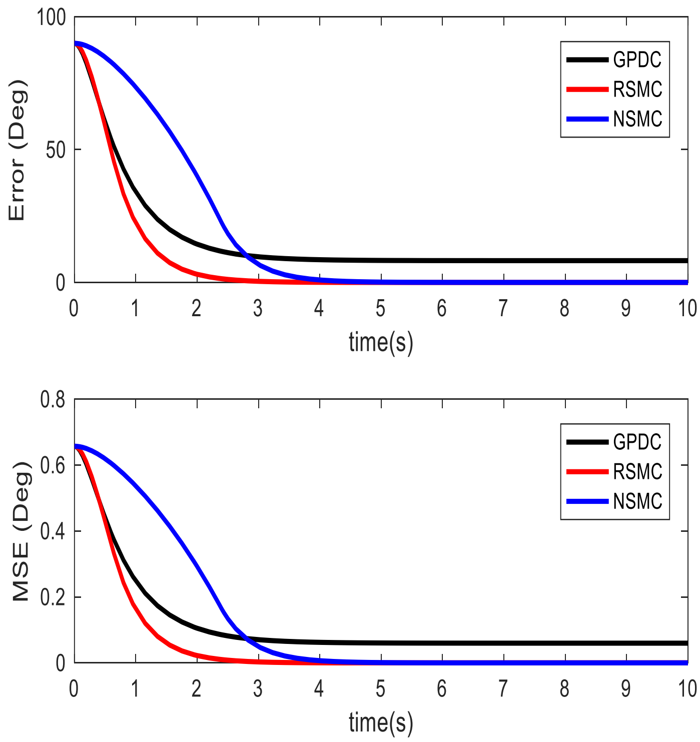

Figure 5. Error graph considering disturbance.

The tracking response parameters of the system with the friction disturbance were as shown in Figure 4 and Table 2. Figure 5 shows the levels of errors during the evaluation. The cumulative errors for the different schemes are as follows: 31^0 with the GPDC, 250 with the RSMC, and 26^0 with the NSMC, as indicated by the summation of errors in Figure 5. The GPDC maintains a steady-state error of about 10^0, making it inaccurate and unable to compensate for the friction introduced into the system. It became the least accurate among the control schemes evaluated. The system response with the RSMC and NSMC approaches, with sudden changes, yielded results similar to those before and were better than with the GPDC, with the RSMC being superior. The tracking responses of the system with frictional disturbance were also similar for the RSMC and the NSMC, and still maintained the superiority observed in the previous results compared to the GPDC.

Table 2. Considering disturbance results.

Parameter	**Control Method**		
	GPDC	**RSMC**	**NSMC**
Settling time (s)	3	1.5	3
Steady State error (^{0})	10^0	0^0	0^0
Rise time (s)	2	0.5	3
Overshoot (%)	Undershoot 10^0	0	0
Peak time (s)	3	2	3.5

The lower tracking errors with the RSMC and the NSMC indicated that the system performance is more accurate than with the GPDC. The similarities in the results of the RSMC and the NSMC are a clear indication that the RSMC maintains almost the same accuracy and robustness as the NSMC despite its simplification. The tracking responses of the system, with all control schemes, approach zero with time regardless of the presence of any disturbance. Hence, it indicated that the system was stable for all the methods examined.

4. Conclusions

The studies on the simplification of the constant-rate sliding-mode controller for a single-link planar robot were carried out successfully. Enhanced precision in robotic system operation can be achieved through control systems. Nonlinear control schemes offer higher accuracy and robustness but are complex. Hence, the constant-rate-reaching law-based sliding mode controller was simplified and applied to the single-link planar robot system. The simplified controller RSMC is compared with the normal version, NSMC, and the gain-scheduling-based PD controller, GPDC. The system performance with and without disturbances was observed, and the disturbance considered was a Coulomb friction disturbance, causing an error of about 10^0. The entire study was conducted via simulation using the SIMULINK/MATLAB software. Results showed that the proposed controller (RSMC) has a shorter algorithm length than the normal SMC (NSMC).

The algorithm was reduced by more than 50%; hence, the RSMC algorithm is shorter and has lower execution time. It meant that it would have a lower computational burden. The settling time, rise time, overshoot, cumulative error, and peak time were 1.5s, 0.5s, 0%, 14^0, and 2.0s, respectively, with the RSMC.

The parameters were: 2s, 1.8s, 0%, 21^0 and 2.0s respectively with the NSMC. The values with the GPDC were: 2.5s, 1.8s, 0%, 22^0 and 3.0s respectively. The mentioned parameters were not considered with disturbance effects. The case considering disturbance effects was as follows: 1.5s, 0.5s, 0%, 25^0, and 2.0s, respectively, with the RSMC, yielding results similar to those without disturbance, except for the cumulative error. The parameter values were: 3.0s, 3.0s, 0%, 26^0 and 3.5s respectively with the NSMC. The parameters with the GPDC were: 3.0s, 2.0s, 11% (10^0 undershoot), 31^0 and 3.0s respectively. The parameters were lowest with the RSMC, followed by the NSMC, and then with the GPDC. The realised and the normal sliding mode controllers have very close results. This indicated that the simplified version also maintains the fastness, accuracy and robustness of the original algorithm. These can be seen in the rise and settling times, which determine the response's speed. The peak time, overshoot, and steady-state error are taken care of to ensure accuracy. Information on robustness is revealed by comparing responses with and without disturbance. The RSMC was the best in compensating for the disturbance introduced, making it superior among the control schemes considered. It tried to maintain its response parameters, both with and without disturbance consideration, but they deteriorated compared to the other schemes, with the GPDC being the worst. The responses of the system with the RSMC and NSMC controllers are better than with the GPDC, both with and without disturbances considered. Therefore, the results showed the ability of the RSMC to enhance performance, and it is expected that, with further refinement, it could be applied not only to this type of system but also to similar and related systems.

Acknowledgments: The authors would like to acknowledge the support of the College of Engineering and Technology, University of Technology and Applied Sciences, Al-Musannah, Oman. The authors also appreciate the support of their respective institutions.

Data Availability Statement: The Data supporting this study are generated through simulation using MATLAB/Simulink and are available from the corresponding author upon reasonable request.

Funding: The authors declare that no funding was received for this research.

Declaration of Competing Interest: The authors declare they have no known competing interests.

Research Involving Human/Animal Participants: This article does not involve any studies conducted by authors on animals or human participants.

References

[1] A. R. Lanfranco, A. E. Castellanos, J. P. Desai, and W. C. Meyers, "Robotic Surgery: A Current Perspective," *Annals of Surgery,* vol. 239, no. 1, pp. 14 - 21, 2004, doi: https://doi.org/10.1097/01.sla.0000103020.19595.7d.

[2] A. A. Gajjar *et al.*, "Evolution of robotics in spine surgery: A historical perspective," *Interdisciplinary Neurosurgery,* vol. 33, p. 101721, 2023, doi: https://doi.org/10.1016/j.inat.2023.101721.

[3] A. Goia, V. Gilard, R. Lefaucheur, M.-L. Welter, D. Maltête, and S. Derrey, "Accuracy of the robot-assisted procedure in deep brain stimulation," *The International Journal of Medical Robotics and Computer Assisted Surgery,* vol. 15, no. 6, p. e2032, 2019, doi: https://doi.org/10.1002/rcs.2032.

[4] L. Furlanetti *et al.*, "Targeting accuracy of robot-assisted deep brain stimulation surgery in childhood-onset dystonia: a

single-center prospective cohort analysis of 45 consecutive cases," (in English), *Journal of Neurosurgery: Pediatrics,* vol. 27, no. 6, pp. 677-687, 01 Jun. 2021 2021, doi: https://doi.org/10.3171/2020.10.PEDS20633.
[5] B. Veejay and B. Dev, "Robotics in neurosurgery," *The Annals of The Royal College of Surgeons of England,* vol. 100, no. 6, pp. 23-26, 2018, doi: https://doi.org/10.1308/rcsann.supp1.19.
[6] A. Grau, M. Indri, L. L. Bello, and T. Sauter, "Industrial robotics in factory automation: From the early stage to the Internet of Things," in *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, 29 Oct.-1 Nov. 2017 2017, pp. 6159-6164, doi: https://doi.org/10.1109/IECON.2017.8217070.
[7] M. Li, A. Milojević, and H. Handroos, "Robotics in Manufacturing—The Past and the Present," in *Technical, Economic and Societal Effects of Manufacturing 4.0: Automation, Adaption and Manufacturing in Finland and Beyond*, M. Collan and K.-E. Michelsen Eds. Cham: Springer International Publishing, 2020, pp. 85-95, doi: https://doi.org/10.1007/978-3-030-46103-4_4
[8] A. Hassan, A. A. Al-Ahdal, A. w. A. Saif, and J. U. Yahaya, "Analysis of Robust Control Method for Single Link Flexible Manipulator," in *2024 21st International Multi-Conference on Systems, Signals & Devices (SSD)*, 22-25 April 2024 2024, pp. 465-473, doi: https://doi.org/10.1109/SSD61670.2024.10548073.
[9] M. Mohamed, F. Anayi, M. Packianather, B. A. Samad, and K. Yahya, "Simulating LQR and PID controllers to stabilise a three-link robotic system," in *2022 2nd International Conference on Advance Computing and Innovative Technologies in Engineering (ICACITE)*, 28-29 April 2022 2022, pp. 2033-2036, doi: https://doi.org/10.1109/ICACITE53722.2022.9823512.
[10] P. Boscariol, A. Gasparetto, and V. Zanotto, "Model Predictive Control of a Flexible Links Mechanism," *Journal of Intelligent and Robotic Systems,* vol. 58, no. 2, pp. 125-147, 2010, doi: https://doi.org/10.1007/s10846-009-9347-5.
[11] N. M. Tahir, S. M. Hassan, Z. Mohamed, and A. G. Ibrahim, "Output based input shaping for optimal control of single link flexible manipulator," *International Journal on Smart Sensing and Intelligent Systems,* vol. 10, no. 2, pp. 1-20, 2017, doi: https://doi.org/10.21307/ijssis-2017-216.
[12] G. Then Mozhi, M. Banu Sundareswari, and K. Dhanalakshmi, "Bidirectional Position Control of a Prismatic joint for Motorized Single Link Robotic Arm Using Adaptive Super- Twisting Sliding Mode Control," *Journal of The Institution of Engineers (India): Series B,* vol. 104, no. 5, pp. 1035-1042, 2023, doi: https://doi.org/10.1007/s40031-023-00908-w.
[13] P. N. Dao, N. T. Dang, T. L. Nguyen, and G. K. Dinh, "Finite-time sliding mode Control strategies for perturbed input-constrained nonlinear bilateral teleoperation systems with variable-time communication delays," *Intelligent Service Robotics,* vol. 18, no. 2, pp. 363-378, 2025, doi: https://doi.org/10.1007/s11370-025-00590-5.
[14] H. G. Dirara, F. T. Yareshe, and C. M. Abdissa, "Design and Analysis of Adaptive Fuzzy Super-Twisting Sliding Mode Controller for Uncertain 2-DOF Robotic Manipulator," *IEEE Access,* vol. 13, pp. 110241-110254, 2025, doi: https://doi.org/10.1109/ACCESS.2025.3581449.
[15] J. Ji and P. Jiang, "Research on Predefined Time Sliding Mode Control Method for High-Speed Maglev Train Based on Finite Time Disturbance Observer," *Actuators,* vol. 14, no. 1, p. 21, 2025, doi: https://doi.org/10.3390/act14010021.
[16] A. H. Mhmood and M. N. Mahyuddin, "H∞ Sliding Mode Control: A Recent Review of Applications and Design Methods," *IEEE Access,* vol. 13, pp. 136687-136715, 2025, doi: https://doi.org/10.1109/ACCESS.2025.3594707.
[17] N. Cherigui, A. Chemidi, A. Tahour, and M. Horch, "A new advanced third-order sliding mode control with adaptive gain adjustment using fuzzy logic technique for standalone photovoltaic systems," *AIMS Electronics and Electrical Engineering,* vol. 9, no. 2, pp. 243-259, 2025, doi: https://doi.org/10.3934/electreng.2025012.
[18] H. Sira-RamÍRez, "On the dynamical sliding mode control of nonlinear systems," *International Journal of Control,* vol. 57, no. 5, pp. 1039-1061, 1993, doi: https://doi.org/10.1080/00207179308934429.
[19] C. L. Phillips, H. T. Nagle, and A. Chakrabortty, *Digital control system analysis and design*. England: Prentice Hall Press, 2015.
[20] J. Liu and X. Wang, "Advanced Sliding Mode Control," in *Advanced Sliding Mode Control for Mechanical Systems: Design, Analysis and MATLAB Simulation*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, pp. 81-96, doi: https://doi.org/10.1007/978-3-642-20907-9_3