

Proceeding Paper

# Sliding Mode Control for Trajectory Tracking of a TurtleBot3 Mobile Robot in Obstacle Environments <sup>†</sup>

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**Abstract:** The proposed work presents a Sliding Mode Controller (SMC) for trajectory tracking of a TurtleBot3 Burger mobile robot based on sliding mode. Trajectory tracking is performed in congested environments; therefore, an obstacle avoidance strategy is presented to prevent the robot from colliding with obstacles. A clear and detailed methodology is developed for the design of the SMC controller with a PID sliding surface for trajectory tracking that can be extrapolated to position control and posture control. The discontinuous part of the SMC is used to ensure that the robot tends to the desired reference whenever an obstacle appears. The stability analysis of the proposed controller is presented, and the experimental results are shown, demonstrating the good performance of the controller.

**Keywords:** TurtleBot3 mobile robot; sliding mode control; obstacle avoidance; trajectory tracking; robust control

## 1. Introduction

Nowadays, robots have received remarkable consideration and application in various sectors, such as industrial, service, agriculture, and medicine, among others. The intelligent navigation of wheeled mobile robots is one of the important characteristics that have been of interest to researchers, together with their mobility capacity, their simple structure, their low cost, and their use in different environments that are difficult to access or that represent a risk to human beings [1,2]. This has enabled robots to play a crucial role in these fields, such as agriculture, industry, and medicine [3]. In recent years, research has increased into control strategies to address the challenges of controlling mobile robots, including trajectory tracking and path following, as well as comparative studies of controllers for tracking tasks.

In this context, several control strategies have been published concerning trajectory tracking of differential drive mobile robots. Classical techniques such as PID have been widely used for trajectory tracking control of mobile robots [4]. Advanced versions, such as PID fractional optimization employing particle swarm algorithms, have been developed [5,6]. Reference [7] proposes a retroactive PID to control both virtual velocity and angular velocity for trajectory tracking. Other approaches employ both the kinematic model combined with Lyapunov [8] for designing controllers that account for input saturation constraints. Additionally, ref. [9] employs a Lyapunov-based control for four-wheeled omnidirectional robots employing the dynamic model, and [10] a similar SMC is used for the four-wheeled robot at the simulation level. A proposed SMC aimed at suppressing the influence of electromechanical systems by feedback of the vortex and sliding mode algorithm is introduced in [11]. Meanwhile, ref. [12] considers a hybrid control approach that contemplates a virtual controller for the kinematic model to address stabilization and



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tracking, along with a fuzzy logic controller to handle uncertainties or uncertain parameters, combining the techniques to improve the robustness of the SMC and the flexibility of fuzzy logic to contribute to the control objective. Other control techniques have been widely implemented with an SMC due to their excellent results, such as the SMC controller presented in [13], which is designed for trajectory tracking for a finite time period, demonstrating its robustness in handling disturbances. Ref. [14] presents an SMC for trajectory tracking combined with an LQR algorithm to decrease the chattering. To achieve improved performance and effectiveness, the SMC has been combined with other control techniques. In [15], the combination of an SMC with neural networks to compensate for external disturbances in velocity tracking, along with a kinematic controller for pose tracking, allows for a significant improvement in handling variable conditions. Similarly, considering that obstacle avoidance plays an important role in mobile robot applications, several strategies have been developed for unstructured environments. Notable approaches include [16], which combines an online tuning of PID parameters without requiring a robot model for obstacle avoidance. Fuzzy logic has also been used for static obstacle avoidance [17], providing a flexible method to manage such events. Additionally, ref. [18] implements a detection algorithm based on YOLO-v4 combined with reinforcement learning for tuning PID controller parameters. Given its potential, the SMC has been considered alongside other algorithms for obstacle avoidance through bilateral teleoperation [19], denoting that the SMC can be effectively integrated with other control techniques to improve the results. It is worth noting that all the cited contributions have presented simulation-level results; thus, implementing a robust control algorithm, like the SMC, in real environments would allow for understanding the real behavior of these controllers, even more when environments with obstacles become a challenge, especially for the calibration and switching of the controller.

Therefore, this work presents the implementation of a Sliding Mode Controller for trajectory tracking of a TurtleBot3 Burger mobile robot in obstacle environments. Unlike previous studies, this work develops a clear and detailed methodology for the design of the SMC controller with a PID sliding surface for trajectory tracking, which can also be extrapolated to position control and posture control. Another contribution of this work is the use of the discontinuous part of the SMC to ensure that the robot tends to the desired reference every time an obstacle appears. A key challenge addressed in this study is the calibration of the controller parameters. The experimental implementation evidenced the criticality of the calibration of this controller; finally, the experimental results demonstrate the controller's strong performance.

This document is structured as follows. Section 2 describes the kinematic model of the mobile robot; Section 3 presents the design and stability analysis of the SMC controller for trajectory tracking and the implemented obstacle avoidance strategy; and Section 4 presents the experimental results in an environment with obstacles. Finally, the conclusions of this work are given.

## 2. Modeling

The mobile robot used in this work is illustrated in Figure 1, corresponding to a TurtleBot3 Burger that has several features [20]. As shown in Table 1, its use is for educational and research purposes. This mobile platform corresponds to a differential traction-type robot; its locomotion system is based on the use of two wheels.



**Figure 1.** TurtleBot3 Burger mobile robot.

**Table 1.** TurtleBot3 Burger mobile robot technical specifications.

| Technical Feature                 | Description                              |
|-----------------------------------|--|
| Size (length × width × height)    | 138 mm × 178 mm × 192 mm                 |
| Weight (+SBC + battery + sensors) | 1 kg                                     |
| Maximum velocities                | 0.22 m/s, 2.84 rad/s                     |
| Single board computers            | Raspberry Pi                             |
| Motors (2 units)                  | Dynamixel (XL430-W250-T)                 |
| Laser distance sensor (LDS)       | 360° LDS-1                               |
| Wheels (2 units)                  | Sprocket wheels for tire, diameter 66 mm |
| Battery                           | Lithium polymer 11.1 V, 1800 mAh         |
| Operating time (battery)          | 2 h:30 min                               |

The improved kinematic model of the mobile robot with a non-holonomic constraint is given by its compact form [21] as follows:

$$\dot{h} = J U \tag{1}$$

where  $\dot{h} = [\dot{x} \ \dot{y}]^T$  is the time variation of position in  $x$  and  $y$  and  $U = [u \ \omega]^T$  are the linear and angular velocities, respectively.  $J$  is the Jacobian rotation matrix and is given by the following:

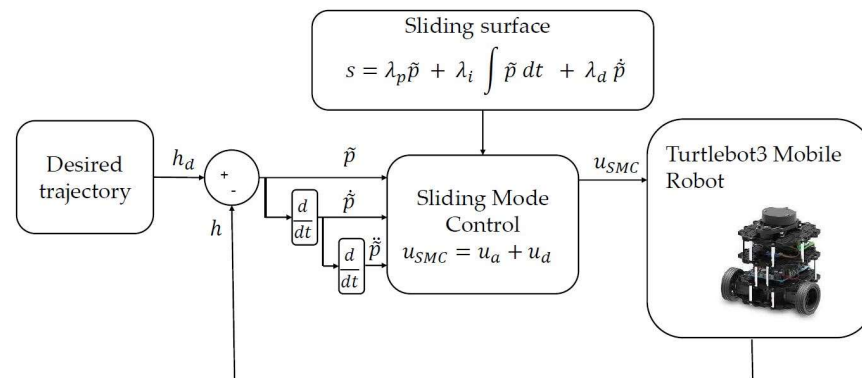
$$J = \begin{bmatrix} \cos(\psi) & -a\sin(\psi) \\ \sin(\psi) & a\cos(\psi) \end{bmatrix} \tag{2}$$

$\psi$  is the orientation of the mobile robot and  $a$  is the distance between the point of interest and the center of the axis joining the wheels.

### 3. Controller

#### 3.1. Sliding Mode Controller (SMC)

The schematic of the Sliding Mode Control strategy is presented in Figure 2, where  $h_d = [x_d \ y_d]^T$  is the desired position;  $h = [x \ y]^T$  is the position of the robot;  $\tilde{p} = (h_d - h) = [\tilde{x} \ \tilde{y}]$  is the tracking error of  $x$  and  $y$ , respectively;  $\dot{\tilde{p}}$  corresponds to the first derivative of the position error; and  $\ddot{\tilde{p}}$  represents the second derivative of the position error.



**Figure 2.** Sliding Mode Control scheme (SMC).

The Sliding Mode Controller is given by the following:

$$u_{SMC} = u_a + u_d \tag{3}$$

where  $u_a, u_d$  correspond to the continuous and discontinuous part, respectively.

For the design of the controller, the sliding surface  $s$  is set, which is given by the following:

$$s = \lambda_p \tilde{p} + \lambda_i \int \tilde{p} dt + \lambda_d \dot{\tilde{p}} \quad (4)$$

where  $\lambda_p$ ,  $\lambda_i$ , and  $\lambda_d$ , are the proportional, integral, and derivative constants, respectively. Deriving (4), we have the following:

$$\dot{s} = \lambda_p \dot{\tilde{p}} + \lambda_i \tilde{p} + \lambda_d \ddot{\tilde{p}} \quad (5)$$

The velocity error is given by  $\dot{\tilde{p}} = \dot{h}_d - \dot{h}$ , replacing (5) as follows:

$$\dot{s} = \lambda_p (\dot{h}_d - \dot{h}) + \lambda_i \tilde{p} + \lambda_d \ddot{\tilde{p}} \quad (6)$$

Replace (1) in (6).

$$\dot{s} = \lambda_p (\dot{h}_d - JU) + \lambda_i \tilde{p} + \lambda_d \ddot{\tilde{p}} \quad (7)$$

For the system to remain inside the sliding surface, we define  $\dot{s} = 0$ , while to obtain  $u_a$ , we consider that  $u_d = 0$ . In a closed loop, we have  $u_{SMC} = u_a$ . Replacing (7), one has the following:

$$0 = \lambda_p (\dot{h}_d - Ju_a) + \lambda_i \tilde{p} + \lambda_d \ddot{\tilde{p}} \quad (8)$$

By clearing  $u_a$ , we obtain the following:

$$u_a = J^{-1} \left[ \dot{h}_d + \frac{\lambda_i}{\lambda_p} \tilde{p} + \frac{\lambda_d}{\lambda_p} \ddot{\tilde{p}} \right] \quad (9)$$

To calculate  $u_d$ , we consider the Lyapunov candidate function  $V = \frac{1}{2} s^T s$ , where its derivative is  $\dot{V} = s^T \dot{s}$ ; replacing (7) in  $\dot{V}$ , we have the following:

$$\dot{V} = s^T \left[ \lambda_p (\dot{h}_d - JU) + \lambda_i \tilde{p} + \lambda_d \ddot{\tilde{p}} \right] \quad (10)$$

Replace (3) and (9) in (10) and develop the following:

$$\dot{V} = -s^T J u_d \quad (11)$$

Therefore,  $u_d$  can be defined as follows:

$$u_d = J^{-1} k \text{sig}(s); k > 0 \quad (12)$$

Replace (12) in (11).

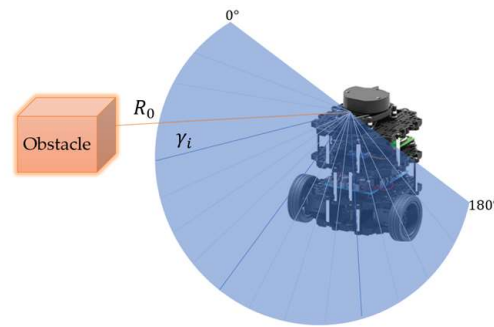
$$\dot{V} = -s^T k \text{sig}(s) \quad (13)$$

where  $\dot{V} < 0$ ; hence,  $s \rightarrow 0$  with  $t \rightarrow \infty$ . Analyzing (4) for  $s = 0$  and since we have a polynomial of two degrees, we have  $\tilde{p} \rightarrow 0$ . When the roots are  $r = \frac{-\lambda_p - \sqrt{\lambda_p^2 - 4\lambda_d\lambda_i}}{2\lambda_d}$ , the following must be fulfilled:  $\lambda_p^2 > 4\lambda_d\lambda_i$ .

### 3.2. Obstacle Avoidance Strategy

Among the characteristics of the TurtleBot3 Burger is that it has a LiDar-type distance sensor capable of scanning 360° of its environment to perform a sweep for SLAM or navigation applications; it reaches a detection distance from 12 to 350 cm with a sampling rate of 1.8 kHz. For the implementation of the obstacle avoidance strategy, a 180° sweep seen from the front of the robot has been considered in order to avoid obstacles that may appear when the robot is executing the trajectory tracking.

Obstacle detection is performed when the LiDAR sensor emits a laser light pulse and determines the distance  $\gamma_i$  through the delay between emission and bounce off an object; in this case, the obstacle towards the sensor is shown in Figure 3.



**Figure 3.** Obstacle avoidance scheme.

The following consideration is established to determine the detection of the obstacle:

$$u_{SMC} = \begin{cases} u_a + u_d \gamma_i < R_o \\ u = 0.05 \left[ \frac{m}{s} \right], \omega = 0.5 \left[ \frac{rad}{s} \right], \gamma_i \geq R_o \end{cases}$$

where  $R_o$  represents the distance from the robot to the obstacle. In the case of obstacle detection, only the LiDAR beams that are smaller than the radius  $R_o$  are taken into consideration, which depends on the value that is set for the detection.

#### 4. Test

In order to evaluate the trajectory tracking of the TurtleBot3 Burger mobile robot using the SMC controller, experimental tests were performed for a circular trajectory described by  $h_d = [x_d \ y_d]$ ;  $y_d = 0.5 \sin\left(\frac{t}{10}\right) + \frac{1}{2}$ ; and  $x_d = 0.5 \cos\left(\frac{t}{10}\right) + \frac{1}{2}$ . Based on the expertise in the management of the SMC controller, the initial parameters that were considered were  $\lambda_{p0} = 1$ ,  $\lambda_{i0} = 1$  and  $\lambda_{d0} = 0.1$ . After the implementation of the tests, the respective calibration was carried out based on the index of the integral square error (ISE) of said parameters, and the values that were used in the tests were obtained as follows:  $\lambda_p = 1$ ,  $\lambda_i = 0.5$  and  $\lambda_d = 0.000001$ . For obstacle avoidance,  $\gamma_i = 15$  cm. The experiment has a duration of 90 s and considers the incorporation of two obstacles within the desired trajectory. The physical obstacle used is a wooden box measuring  $10 \times 10 \times 30$  cm (width, length, and height) with a hollow structure that weighs 0.500 kg.

##### 4.1. SMC Controller Test

This section presents the results of experimental tests for the trajectory tracking of the TurtleBot3 Burger mobile robot using an SMC controller considering obstacle avoidance.

##### 4.1.1. Described Trajectory

Figure 4 shows the desired trajectory and the actual trajectory of the mobile robot during the experiment. With the results obtained, it is observed that at the beginning of the trajectory, the mobile robot is positioned to follow the circular trajectory. Once the robot is aligned with the trajectory, there is a perfect tracking of the trajectory. Likewise, in the presence of an obstacle, the robot executes the obstacle avoidance strategy, deviating its trajectory to avoid a collision; once it avoids the obstacle, the SMC control positions the robot again on the desired trajectory.

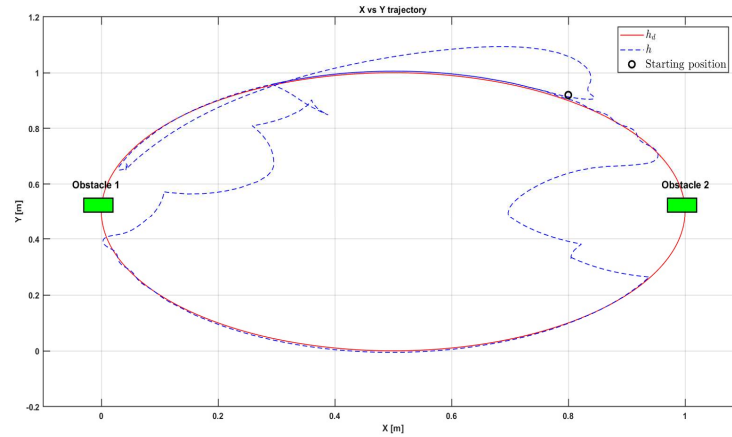


Figure 4. Circular trajectory described by the mobile robot.

#### 4.1.2. Mobile Robot Velocities

Figure 5 shows linear velocity  $u$ . At the beginning, it exhibits high values of 0.2 m/s as the robot tries to align itself with the desired trajectory from the initial position. Once the robot reaches the desired trajectory, the velocity remains constant at approximately 0.025 m/s. Between 19 and 31 s, obstacle 1 appears, during which the linear velocity drops to 0 m/s due to the detection of obstacle 1; this causes the robot to stop and start and turn to avoid a collision. Once the robot turns and the obstacle disappears from its path, the robot attempts to return to the trajectory, resulting in spikes in linear velocity as it strives to reach the reference. However, as the robot turns, it encounters obstacle 1 again, causing fluctuations in linear velocity until it completely avoids the obstacle. A similar pattern occurs between 57 and 66 s, where obstacle 2 is present. In other intervals, the robot continues along the trajectory at a velocity of approximately 0.025 m/s.

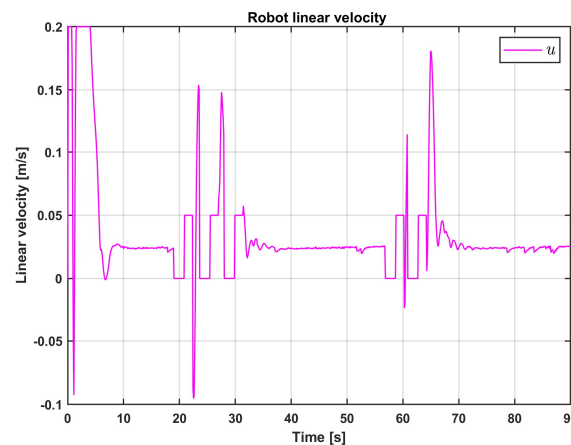


Figure 5. Robot linear velocity.

Figure 6 shows the angular velocity of the mobile robot. In the interval from 0 to 9 s, there are peaks in angular velocity as the TurtleBot3 Burger reaches the circular trajectory. During the interval from 9 to 19 s, the angular velocity fluctuates between 0.1 and 0.15 rad/s, indicating that the robot is following the circular trajectory. In the interval from 19 to 31 s, when obstacle 1 is present, the robot's angular velocity increases to 0.5 rad/s to avoid the obstacle, causing the robot to temporarily deviate from the trajectory. Once the robot turns and the obstacle is no longer in its path, it attempts to return to the trajectory, resulting in spikes in angular velocity as it seeks to reacquire the trajectory. As the robot turns, it encounters obstacle 1 again, leading to further changes in angular velocity until it fully avoids the obstacle. A similar pattern is observed between 57 and 66 s, where

obstacle 2 is present. In other intervals, the robot continues following the trajectory with an angular velocity of approximately 0.05 rad/s.

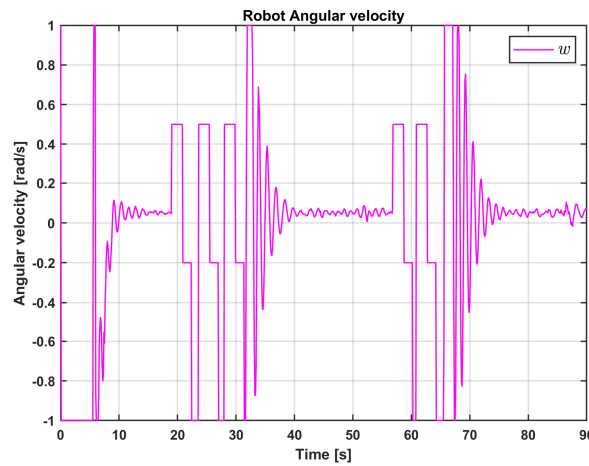


Figure 6. Robot angular velocity.

Figure 7 presents the position error,  $\tilde{x}$ . In the interval from 0 to 9 s, the mobile robot starts from the initial position and tries to align to the desired trajectory, generating an approximate maximum error of 0.9 m. In the interval from 9 to 19 s, the robot reaches the desired trajectory, which reduces the position error  $\tilde{x}$  to approximately 0.05 m. However, at the instant from 19 s to 31 s, the robot detects obstacle 1, causing it to temporarily deviate from the circular trajectory, and the position error  $\tilde{x}$  fluctuates until it returns to the desired trajectory. Similarly, this happens between 57 and 66 s, and the position error  $\tilde{x}$  increases and shows oscillating behavior due to the avoidance of obstacle 2.

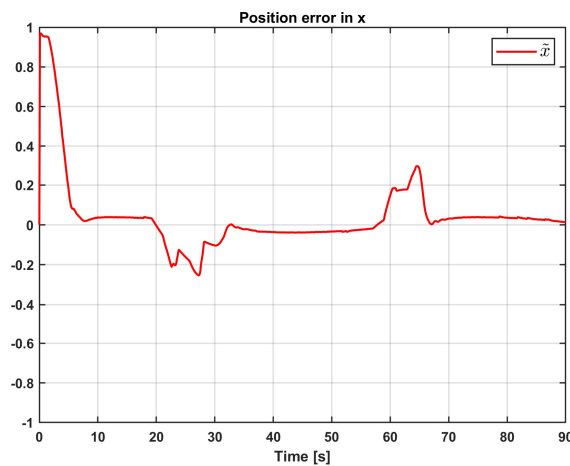
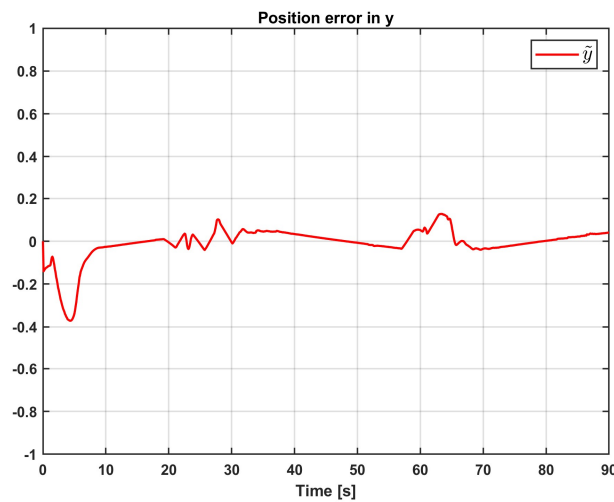


Figure 7. Position errors,  $\tilde{x}$ .

Figure 8 presents the position error,  $\tilde{y}$ . It is observed that in the interval from 0 to 9 s, the mobile robot is in search of the desired trajectory, which causes oscillations in the position error in  $y$ . During 9 to 19 s, the error gradually increases until it reaches a value of approximately 0.01 m. In the interval from 19 to 31 s, the  $y$ -position error presents oscillations due to the fact that the robot temporarily deviates from the trajectory while avoiding obstacle 1; the same happens in the interval from 57 to 66 s, where it detects obstacle 2. For the rest of the time, the error value is a maximum of approximately 0.02 m.



**Figure 8.** Position errors,  $\tilde{y}$ .

## 5. Discussion

The SMC controller proposed for the trajectory tracking of the mobile robot TurtleBot3 Burger presents good trajectory tracking without obstacles, and the linear and angular velocities do not present oscillations and tend to have values of 0.025 m/s and 0.15 rad/s, respectively. This allows the errors in  $x$  and  $y$  to have maximum values of 0.05 m, which are values expected by the odometry of the robot. When the obstacles are presented in the trajectory in the intervals from 19 to 31 s and 57 to 66 s, position errors in  $x$  and  $y$  are shown in Figures 7 and 8, causing the robot to temporarily deviate from the trajectory to avoid colliding with the obstacle, generating an error 0.3 m and 0.15 m in  $x$  and  $y$ , respectively, which is expected for the robot to avoid the obstacle. Likewise, the robot speeds in these intervals are oscillatory to avoid colliding with the obstacle.

## 6. Conclusions

This work presented the implementation of the Sliding Mode Controller for trajectory tracking of a TurtleBot3 Burger mobile robot in a congested environment. A clear and detailed methodology of the design of the SMC controller with a PID sliding surface for trajectory tracking is provided; this controller can be used for position control, and the methodology can be extrapolated to develop posture control. An obstacle avoidance strategy was implemented, which caused the robot to temporarily deviate from the trajectory. The discontinuous part of the SMC was utilized to ensure that the robot returns to the desired reference whenever it deviates from the intended trajectory to avoid obstacles. The calibration of the controller parameters was carried out based on experimental tests to achieve the smallest possible error. The experimental results demonstrate the controller's strong performance. The main disadvantage of the implemented controller is its challenging calibration, which could be addressed in future work through optimization techniques for controller calibration.

**Author Contributions:** This work presents the implementation of the Sliding Mode Controller for trajectory tracking of a TurtleBot3 Burger mobile robot in a congested environment. Conceptualization: G.M.A. and P.L.; investigation and methodology: S.C. and M.P.; design of control laws: G.M.A. and P.L.; software and validation: J.R. and S.C.; writing—original draft preparation: J.R., S.C. and M.P.; writing—review and editing: G.M.A. and P.L.; Supervision: P.L. All authors have read and agreed to the published version of the manuscript.

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**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Thai, T.T.N.; Le, Q.T.T.; Nguyen, C.V.; Nguyen, M.T.; Nguyen, X.T.; Phan, G.T.; Nguyen, T.S.; Pham, V.C. Autonomous Mobile Robot: Navigating and Monitoring Fire Safety at Power Substations. In Proceedings of the 2022 7th National Scientific Conference on Applying New Technology in Green Buildings (ATiGB), Da Nang, Vietnam, 11–12 November 2022; pp. 117–182. [\[CrossRef\]](#)
2. Mohamed, J.; Sheik, A.; Venusamy, K.; Ramanathan, K. Optimization of an Intelligent and Survey Robot for Inspection and Fault Diagnosis Mechanism in the Manufacturing Sector. In Proceedings of the 2022 3rd International Conference on Electronics and Sustainable Communication Systems (ICESC), Coimbatore, India, 17–19 August 2022. [\[CrossRef\]](#)
3. Baskoro, C.H.A.H.B.; Saputra, H.M.; Mirdanies, M.; Susanti, V.; Radzi, M.F.; Aziz, R.I.A. An Autonomous Mobile Robot Platform for Medical Purpose. In Proceedings of the 2020 International Conference on Sustainable Energy Engineering and Application (ICSEEA), Tangerang, Indonesia, 18–20 November 2020; pp. 41–44. [\[CrossRef\]](#)
4. Ramasamy, S.; Senthilkumar, N.; Karpagam, S.; Ramani, U.; Swetha, B. Embedded PID Controller Design Based Self Adjusting Robot. In Proceedings of the 2022 Second International Conference on Artificial Intelligence and Smart Energy (ICAIS), Coimbatore, India, 23–25 February 2022; pp. 1531–1536. [\[CrossRef\]](#)
5. Du, J.; Song, B.; Xu, L. Design of Fractional-order PID Controller for Path Tracking of Wheeled Mobile Robot. In Proceedings of the 2021 China Automation Congress (CAC), Beijing, China, 22–24 October 2021; pp. 8019–8023. [\[CrossRef\]](#)
6. Salinas, L.R.; Santiago, D.; Slawiński, E.; Mut, V.A.; Chavez, D.; Leica, P.; Camacho, O.; Salinas, L.R.; Santiago, D.; Slawiński, E.; et al. P+d Plus Sliding Mode Control for Bilateral Teleoperation of a Mobile Robot. *Int. J. Control Autom. Syst.* **2018**, *16*, 1927–1937. [\[CrossRef\]](#)
7. Chen, B.; Cao, Y.; Feng, Y. Research on Trajectory Tracking Control of Non-holonomic Wheeled Robot Using Backstepping Adaptive PI Controller. In Proceedings of the 2022 7th Asia-Pacific Conference on Intelligent Robot Systems (ACIRS), Tianjin, China, 1–3 July 2022; pp. 7–12. [\[CrossRef\]](#)
8. Bai, J.; Sun, Z.; Chen, Y. Trajectory tracking control for wheeled mobile robots with input saturation. In Proceedings of the 2020 7th International Conference on Information, Cybernetics, and Computational Social Systems (ICCSS), Guangzhou, China, 13–15 November 2020; pp. 537–540. [\[CrossRef\]](#)
9. Andreev, A.; Peregudova, O. On the Trajectory Tracking Control of a Wheeled Mobile Robot Based on a Dynamic Model with Slip. In Proceedings of the 2020 15th International Conference on Stability and Oscillations of Nonlinear Control Systems (Pyatnitskiy's Conference) (STAB), Moscow, Russia, 3–5 June 2020; pp. 1–4. [\[CrossRef\]](#)
10. Moudoud, B.; Aissaoui, H.; Diany, M. Robust trajectory tracking control based on sliding mode of Differential Driving Four-Wheeled Mobile Robot. In Proceedings of the 2020 IEEE 6th International Conference on Optimization and Applications (ICOA), Beni Mellal, Morocco, 20–21 April 2020; pp. 1–5. [\[CrossRef\]](#)
11. Rassadin, Y.; Shinkaryuk, A. Modified Sliding Mode Control for Tracking Problem of Wheeled Mobile Robot. In Proceedings of the 2020 13th International Conference “Management of Large-Scale System Development” (MLSD), Moscow, Russia, 28–30 September 2020; pp. 1–3. [\[CrossRef\]](#)
12. Shi, W.; Xu, L.; Chen, S. Adaptive Dynamic Surface Control for Simultaneous Stabilization and Tracking of Wheeled Mobile Robot. In Proceedings of the 2020 39th Chinese Control Conference (CCC), Shenyang, China, 27–30 July 2020; pp. 381–386. [\[CrossRef\]](#)
13. Yu, H.; Ai, Z.; Sheng, N.; Liu, B. Finite-Time Trajectory Tracking Control of Mobile Robots Based on Dynamic Terminal Sliding Mode. In Proceedings of the 2022 34th Chinese Control and Decision Conference (CCDC), Hefei, China, 21–23 May 2022; pp. 4421–4426. [\[CrossRef\]](#)
14. Chatterjee, M.; Hanif, O.; Deshpande, N.G.; Stancu, A. Trajectory Tracking of a Nonholonomic Mobile Robot using Optimal Cascade Sliding Mode Controller. In Proceedings of the 2020 3rd International Conference on Intelligent Robotic and Control Engineering (IRCE), Oxford, UK, 10–12 August 2020; pp. 81–86. [\[CrossRef\]](#)
15. Gao, H.; Wang, X.; Hu, J. Adaptive Tracking Control of Mobile Robots based on Neural Network and Sliding Mode Methods. In Proceedings of the 2023 38th Youth Academic Annual Conference of Chinese Association of Automation (YAC), Hefei, China, 27–29 August 2023; pp. 962–967. [\[CrossRef\]](#)
16. Pastrana, M.A.; Oliveira, L.H.; Mendes, D.A.; Silva, D.L.; Mendoza-Peñaloza, J.; Muñoz, D.M. Implementation of a PID Controller using Online Tuning Applied to a Mobile Robot Obstacle following/Avoidance. In Proceedings of the 2024 Argentine Conference on Electronics (CAE), Bahia Blanca, Argentina, 7–8 March 2024. [\[CrossRef\]](#)
17. Adam, Y.M.; Sariff, N.B.; Algeelani, N.A. E-puck Mobile Robot Obstacles Avoidance Controller Using the Fuzzy Logic Approach. In Proceedings of the 2021 2nd International Conference on Smart Computing and Electronic Enterprise (ICSCEE), Cameron Highlands, Malaysia, 15–16 June 2021; pp. 107–112. [\[CrossRef\]](#)

18. Mashhouri, S.; Rahmati, M.; Borhani, Y.; Najafi, E. Reinforcement Learning based Sequential Controller for Mobile Robots with Obstacle Avoidance. In Proceedings of the 2022 8th International Conference on Control, Instrumentation and Automation (ICCIA), Tehran, Iran, 2–3 March 2022; pp. 1–5. [[CrossRef](#)]
19. Leica, P.; Balseca, J.; Cbascango, D. Controller Based on Null Space and Sliding Mode (NSB-SMC) for Bidirectional Teleoperation of Mobile Robots Formation in an Environment with Obstacles. In Proceedings of the 2019 IEEE Fourth Ecuador Technical Chapters Meeting (ETCM), Guayaquil, Ecuador, 13–15 November 2019. [[CrossRef](#)]
20. Robots e-Manual TurtleBot3. Available online: <https://emanual.robotis.com/docs/en/platform/turtlebot3/features/> (accessed on 2 September 2024).
21. Leica, P.; Sagnay, B.; Poveda, F.; Camacho, O. Null-Space-Based Controller for Heterogeneous Robot Formation in Congested Environments. In Proceedings of the 2019 International Conference on Information Systems and Computer Science (INCISCOS), Quito, Ecuador, 20–22 November 2019; pp. 238–243. [[CrossRef](#)]

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