TRAJECTORY TRACKING OF A MOBILE ROBOT USING A MAMDANI FUZZY LOGIC CONTROLLER UNDER DISTURBANCE

ĐIỀU KHIỂN BÁM QUỸ ĐẠO CHO ROBOT DI ĐỘNG SỬ DỤNG ĐIỀU KHIỂN MỜ MAMDANI DƯỚI TÁC ĐỘNG CỦA NHIỄU

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Abstract:

This paper presents a fuzzy logic control strategy for trajectory tracking of a differential-drive mobile robot operating in uncertain environments. A Mamdani-type fuzzy inference system is designed with three independent fuzzy controllers to regulate the tracking errors in position and orientation. The controller uses triangular membership functions and a compact set of inference rules to ensure simplicity and computational efficiency. The performance of the proposed method is evaluated through simulation in both disturbance-free and disturbance-rich conditions. In the nominal case, the robot closely follows a predefined sinusoidal trajectory with minimal steady-state error. When subjected to external disturbances, the fuzzy controller maintains accurate tracking and bounded control signals, demonstrating strong robustness and adaptability. The approach does not rely on an exact model of the robot's dynamics, making it practical for real-world deployment. These results confirm the potential of fuzzy logic as an effective solution for mobile robot navigation under uncertainty.

Keywords:

Fuzzy Logic Control; Mamdani Inference; Mobile Robot; Trajectory Tracking; Robustness to Disturbance.

Tóm tắt:

Bài báo này trình bày một chiến lược điều khiển mờ nhằm mục tiêu bám quỹ đạo cho robot di động dẫn động vi sai hoạt động trong môi trường có nhiều bất định. Một hệ suy luận mờ kiểu Mamdani được thiết kế với ba bộ điều khiển mờ độc lập để hiệu chỉnh sai số bám theo về vị trí và phương hướng. Bộ điều khiển sử dụng các hàm thành viên dạng tam giác cùng với một tập luật suy luận gọn nhẹ nhằm đảm bảo tính đơn giản và hiệu quả tính toán. Hiệu suất của phương pháp đề xuất được đánh giá thông qua mô phỏng trong cả hai điều kiện: không có nhiễu và có nhiều nhiễu. Trong trường hợp danh định, robot bám sát quỹ đạo hình sin đã được định trước với sai số xác lập nhỏ. Khi chịu tác động của các nhiễu bên ngoài, bộ điều khiển mờ vẫn duy trì khả năng bám quỹ đạo chính xác và tín hiệu điều khiển bị giới hạn, thể hiện độ bền vững và khả năng thích nghi cao. Phương pháp này không phụ thuộc vào mô hình động lực học chính xác của robot, từ đó tăng tính khả thi khi triển khai *trong thực tế. Các kết quả thu được khẳng định tiềm năng của điều khiển mờ như một giải pháp hiệu quả cho bài toán dẫn đường robot di động trong điều kiện bất định.*

Từ khóa:
Điều khiển mờ, Suy luận Mamdani, Robot di động, Bám quỹ đạo, Khả năng chống nhiễu.

1. INTRODUCTION

Mobile robots have become a cornerstone of modern automation systems due to their flexibility, adaptability, and ability to navigate dynamic environments [1], [2], [3], [4]. Unlike stationary industrial manipulators, mobile robots can move within a workspace, making them ideal for a wide range of applications such as warehouse logistics, service robotics, environmental monitoring, and autonomous vehicles. The increasing demand for intelligent systems capable of interacting with their surroundings in real-time has accelerated research into the control and navigation of mobile robots.

One of the fundamental challenges in mobile robotics is achieving precise and robust trajectory tracking under real-world conditions. Mobile robots often operate in environments with disturbances [5], [6], [7] and modeling uncertainties [8], [9]. These factors pose significant difficulties for the control system, which must ensure stability, accuracy, and responsiveness. To address these challenges, various control approaches have been developed, including proportional–integral–derivative (PID) controllers [10], [11], sliding mode control (SMC) [12], [13], [14], backstepping [15], [16], and model predictive control (MPC) [17], [18]. For handling uncertainties, many methods using adaptive approaches have addressed issues related to tracking control for mobile robots, such as in [19], or approaches based on adaptive dynamic programming [20]. These approaches can efficiently handle model variations due to environmental changes, providing advanced strategies for tracking control in mobile robot systems. While these methods can achieve satisfactory results in many scenarios, they often require accurate modeling and may struggle in the presence of unstructured uncertainties.

Fuzzy logic control (FLC), inspired by human reasoning, has emerged as an effective alternative to model-based techniques. Unlike classical controllers that rely on precise mathematical models, FLC utilizes linguistic rules and membership functions to map input errors to control actions [21], [22], [23]. This feature makes fuzzy controllers particularly suitable for systems with imprecise or poorly defined dynamics. In the context of mobile robots, fuzzy logic control offers robustness, interpretability, and ease of implementation, especially when dealing with uncertain or nonlinear conditions. Additionally, some advanced model-free approaches, such as reinforcement learning [24] or data-driven methods [25], have proven effective in designing tracking control for mobile robots, even under environmental uncertainties and disturbances.

In this study, we propose a trajectory tracking strategy for a mobile robot using a Mamdani fuzzy logic controller. The control framework is composed of three independent fuzzy controllers, each responsible for minimizing the tracking error in one of the pose dimensions (position and orientation). The proposed controller is designed with a minimal yet effective rule base and triangular membership functions to maintain both simplicity and real-time feasibility. Through simulation, we demonstrate that the fuzzy controller can accurately track a predefined trajectory while maintaining bounded control signals and compensating for initial disturbances.

The main contributions of this paper are summarized as follows :

- A fuzzy control scheme is developed to handle the nonlinear kinematics and trajectory tracking of a mobile robot.
- A systematic design of the fuzzy logic controller using triangular membership functions and interpretable inference rules is provided.
- The effectiveness of the proposed controller is validated through simulation results with and without disturbances, demonstrating high tracking accuracy and control smoothness.

The remainder of this paper is organized as follows : Section 2 presents the kinematics of the mobile robot. Section 3 introduces the fuzzy logic controller design, including error transformation, membership functions, and inference rules. Section 4 provides simulation results to evaluate the control performance under a predefined trajectory. Finally, Section 5 concludes the paper and outlines potential future research directions.

2. MODELING

This section presents the kinematic model of the mobile robot used in this study, shown in Figure 1. The robot is assumed to move on a flat two-dimensional plane with non-slipping wheels. The model describes the robot's pose, which includes its position and orientation in the global coordinate system. The relationship between the robot's velocity and wheel angular velocities is also derived to support the design of the control algorithm.

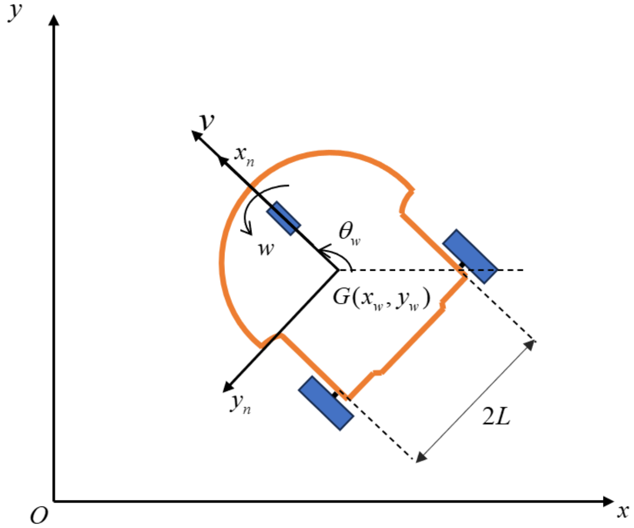

Figure 1. Mobile robot.

Assuming the robot operates in a planar environment, its pose $\boldsymbol{P_w}$ consists of the two-dimensional position $(\boldsymbol{x_w}, \boldsymbol{y_w})$ and the orientation angle $\boldsymbol{\theta_w}$. Accordingly, the position of the mobile robot in the global coordinate system $(\boldsymbol{Oxy})$ can be represented as:

$$P_w = [x_w \quad y_w \quad \boldsymbol{\theta}_w]^T \quad (1)$$

Given that the linear velocity $\boldsymbol{v}$ and angular velocity $\boldsymbol{\omega}$ serve as control inputs, the corresponding equation is expressed as follows:

$$\dot{P}_w = \begin{bmatrix} \dot{x}_w \\ \dot{y}_w \\ \dot{\boldsymbol{\theta}}_w \end{bmatrix} = \begin{bmatrix} cos\boldsymbol{\theta}_w & 0 \\ sin\boldsymbol{\theta}_w & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ \boldsymbol{\omega} \end{bmatrix} \quad (2)$$

where $\dot{\boldsymbol{P}}_{\boldsymbol{w}}$ denotes the instantaneous velocity of the robot's pose in the global frame.

Furthermore, by incorporating the angular velocities of each powered wheel, the control inputs can be defined in terms of wheel angular velocities as follows:

$$v = \frac{\omega_r + \omega_l}{2} R \tag{3}$$

$$\boldsymbol{\omega} = \frac{\omega_r + \omega_l}{2} R \tag{4}$$

$$\boldsymbol{\omega_r} = \frac{2v + \omega L}{2R} \tag{5}$$

$$\boldsymbol{\omega_l} = \frac{2v - \omega L}{2R} \tag{6}$$

Where $\boldsymbol{\omega_r}$ and $\boldsymbol{\omega_l}$ are the angular velocities of the right and left wheels, respectively. The parameters R and L represent the wheel radius and half the distance between the two wheels.

The coordinate system $(x_n G y_n)$ is attached to the mobile robot and rotates with it. The center point $G(x_w, y_w)$ denotes the geometric center of the robot, and $\boldsymbol{\theta}_w$ indicates the robot's orientation relative to the global x-axis.

3. CONTROL DESIGN

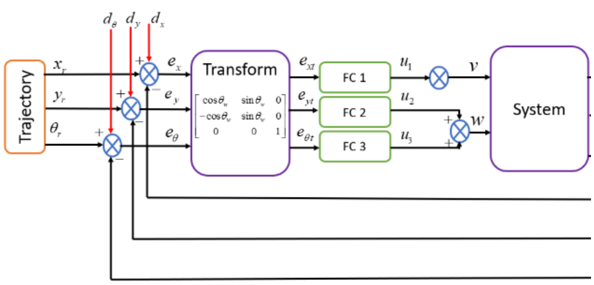

Figure 2. Control structure.

This section presents the control strategy used to drive the mobile robot along a predefined trajectory. A fuzzy logic-based controller is implemented, where the control signals are generated based on pose errors calculated in the robot's local frame. The control structure is shown in Figure 2.

Let $\boldsymbol{x_r}, \boldsymbol{y_r}, \boldsymbol{\theta_r}$ represent the desired position and orientation, while $\boldsymbol{x_w}, \boldsymbol{y_w}, \boldsymbol{\theta_w}$ denote the current pose of the robot. The global pose errors are:

$$\boldsymbol{e_x = x_r - x_w}$$

$$\boldsymbol{e_y = y_r - y_w}$$

$$\boldsymbol{e_\theta = \theta_r - \theta_w}$$

These errors are transformed into the robot's local coordinate frame using the following transformation:

$$\begin{bmatrix} e_{xt} \\ e_{yt} \\ e_{\theta t} \end{bmatrix} = \begin{bmatrix} cos\theta_w & sin\theta_w & 0 \\ -cos\theta_w & sin\theta_w & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e_x \\ e_y \\ e_\theta \end{bmatrix}$$
(7)

A fuzzy logic controller is used to compute the control signals. The controller consists of three fuzzy controllers (FC1, FC2, FC3) corresponding to the three error inputs $\boldsymbol{e_{xt}}$, $\boldsymbol{e_{yt}}$, and $\boldsymbol{e_{\theta t}}$. Each fuzzy controller maps its input to an output signal $\boldsymbol{u_i}$ using five linguistic terms and triangular membership functions. As shown in Figure 2, the desired trajectory for the mobile robot is formulated in advance. To control the mobile robot, measured information about its state including $\boldsymbol{x_w}$, $\boldsymbol{y_w}$, and $\boldsymbol{\theta_w}$ is required. However, these measurements are affected by disturbances, which pose challenges for tracking the desired trajectory. A transformation is applied to establish the tracking error used as feedback for each fuzzy controller. Each controller then generates control signals for the mobile robot. Specifically, the outputs of FC2 and FC3 are combined to form the $\boldsymbol{w}$ signal, while FC1 is used to generate the control signal $\boldsymbol{v}$. With this control structure, the mobile robot can effectively follow the reference trajectory, even in the presence of output disturbances.

The triangular membership functions used for the input variables $\boldsymbol{e_{xt}}$, $\boldsymbol{e_{yt}}$, and $\boldsymbol{e_{\theta t}}$ are defined as follows:

$Very\ Negative\ (VN)$: $[-15,\quad -10,\quad -5]$

$Negative\ (N)$: $[-10,\quad -5,\quad 0]$

$Medium\ (M)$: $[-5,\quad 0,\quad 5]$

$Positive\ (P)$: $[0,\quad 5,\quad 10]$

$Very\ Positive\ (VP)$: $[5,\quad 10,\quad 15]$

The output membership functions of the first fuzzy controller (FC1), which generates the control signal $\boldsymbol{u_1}$, are defined using the following triangular sets:

$Very\ Low\ (VL)$: $[-1500,\quad -1000,\quad -500]$

$Low\ (L)$: $[-1000,\quad -500,\quad 0]$

$Zero\ (Z)$: $[-500,\quad 0,\quad 500]$

$High\ (H)$: $[0,\quad 500,\quad 1000]$

$Very\ High\ (VH)$: $[500,\quad 1000,\quad 1500]$

The output membership functions of the second and third fuzzy controllers (FC2 and FC3), which produce the control signals $\boldsymbol{u_2}$ and $\boldsymbol{u_3}$, are defined as:

$\boldsymbol{Very\ Low\ (VL)}$: $[\boldsymbol{-750},\quad \boldsymbol{-500},\quad \boldsymbol{-250}]$

$\boldsymbol{Low\ (L)}$: $[\boldsymbol{-500},\quad \boldsymbol{-250},\quad \boldsymbol{0}]$

$\boldsymbol{Zero\ (Z)}$: $[\boldsymbol{-250},\quad \boldsymbol{0},\quad \boldsymbol{250}]$

$\boldsymbol{High\ (H)}$: $[\boldsymbol{0},\quad \boldsymbol{250},\quad \boldsymbol{500}]$

$\boldsymbol{Very\ High\ (VH)}$: $[\boldsymbol{250},\quad \boldsymbol{500},\quad \boldsymbol{750}]$

Each fuzzy controller applies the following five inference rules to map the input error values to output control signals:

$$IF\ e_m\ is\ VN\ THEN\ u_i\ is\ VL \tag{8}$$

$$IF\ e_m\ is\ N\ THEN\ u_i\ is\ L \tag{9}$$

$$IF\ e_m\ is\ M\ THEN\ u_i\ is\ Z \tag{10}$$

$$IF\ e_m\ is\ P\ THEN\ u_i\ is\ H \tag{11}$$

$$IF\ e_m\ is\ VP\ THEN\ u_i\ is\ VH \tag{12}$$

In these rules, the variable e_m refers to one of the transformed error signals e_{xt}, e_{yt}, or $e_{\theta t}$, and u_i corresponds to the respective control signal u_1, u_2, or u_3.

$$\left\{ \mu(x) = \begin{cases} 0, & x \le a \\ \frac{x-a}{b-a}, & a < x \le b \\ \frac{c-x}{c-b}, & b < x < c \\ 0, & x \ge c \end{cases} \right. \tag{13}$$

The input range of each controller is $[-10\quad 10]$. The output ranges are:

- $u_1 \in [-1000,\quad 1000]$
- $u_2, u_3 \in [-500,\quad 500]$

Overall, the proposed fuzzy logic controller provides a robust and interpretable approach for mobile robot trajectory tracking. The use of triangular membership functions and a minimal rule base ensures both simplicity and adaptability in the control design. The effectiveness of the controller will be evaluated through simulation results in the following section.

4. SIMULATION AND RESULTS

To evaluate the performance of the proposed fuzzy logic controller, simulations were conducted under two conditions: without disturbances and with external disturbances. The control objective in both cases was to ensure accurate trajectory tracking while maintaining bounded and smooth control inputs.

4.1. Trajectory Tracking Without Disturbance

In the nominal case, the robot follows a predefined sinusoidal trajectory in a disturbance-free environment.

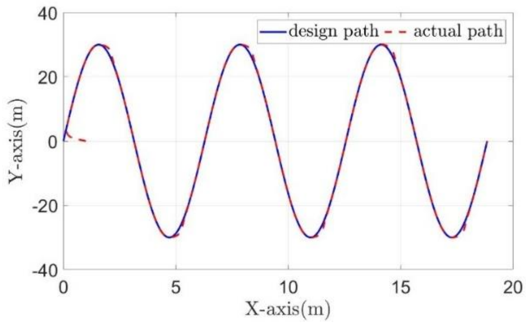

Figure 3. Trajectory tracking without disturbance: reference path (blue) vs. actual path (red).

Figure 3 demonstrates the effectiveness of the controller in maintaining a close match between the robot's actual trajectory and the reference path. The robot follows the sinusoidal trajectory with minimal deviation, highlighting the system's accuracy in ideal conditions.

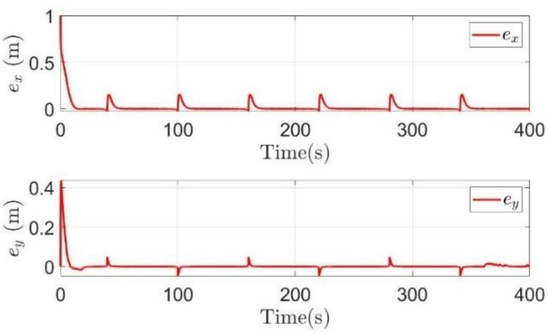

Figure 4. Tracking errors in the x-axis and y-axis over time (without disturbance).

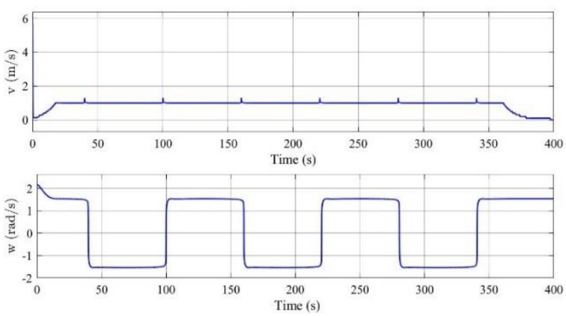

Figure 5. Control signals in the disturbance-free case: linear velocity v (top), angular velocity ω (bottom).

Figure 4 shows that the position errors e_x and e_y are initially nonzero but quickly converge to near-zero values. This indicates the controller's ability to suppress initial offsets and maintain precise tracking.

In Figure 5, both v and ω exhibit smooth transitions and stay within operational limits. The control signals are continuous, with no sudden jumps, reflecting the fuzzy controller's ability to generate stable control actions.

4.2. Trajectory Tracking Under Disturbance

In this scenario, external disturbances are added to the system to assess the robustness of the proposed controller. These disturbances affect the robot's motion, simulating real-world uncertainty.

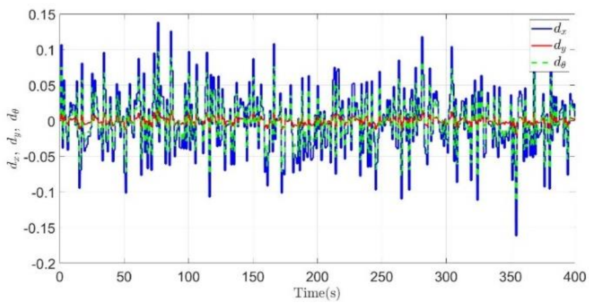

Figure 6. External disturbance signals applied to the system.

Figure 6 illustrates the external disturbances injected into the robot's dynamics. These signals introduce bounded, time-varying perturbations to the motion model, aiming to challenge the controller's robustness.

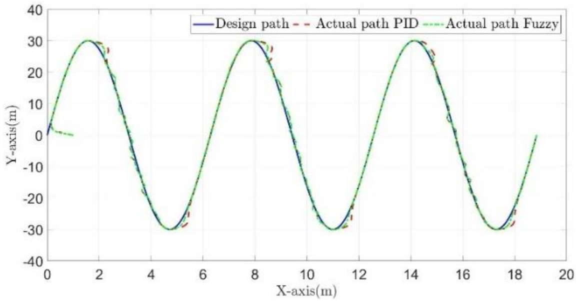

Figure 7. Trajectory tracking under disturbance: reference path (blue), actual path using PID controller (red), and actual path using fuzzy controller (green).

Despite the presence of disturbances, Figure 7 shows that the robot still closely follows the desired trajectory. The deviations are slightly more noticeable than in the disturbance-free case but remain within acceptable bounds.

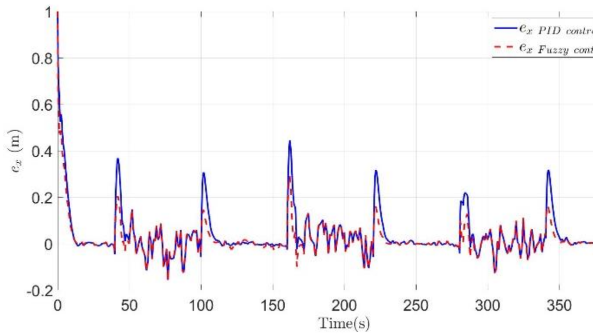

Figure 8. Tracking error in x-axis under disturbance.

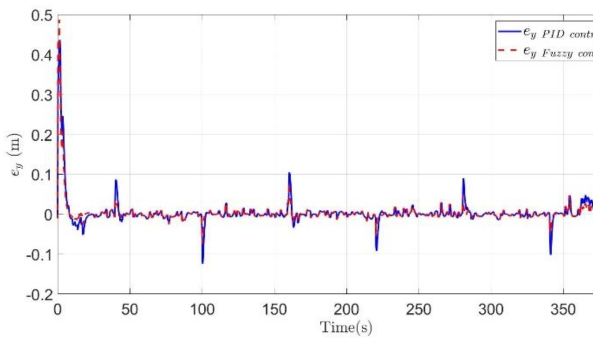

Figure 9. Tracking error in y-axis under disturbance.

Figures 8 and 9 present the tracking errors $\boldsymbol{e_x}$ and $\boldsymbol{e_y}$ under disturbances. The errors show small oscillations due to perturbations but are well-regulated and remain within a tight range, validating the controller's robustness.

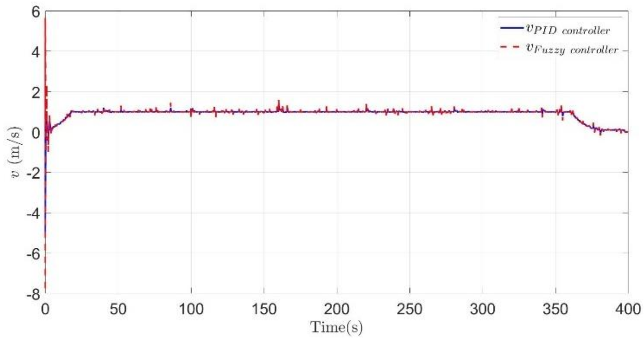

Figure 10. Control signal $\boldsymbol{v}$ (linear velocity) under disturbance.

Figures 10 and 11 show the corresponding control signals under disturbed conditions. While small oscillations appear as the controller reacts to dynamic changes, the signals stay bounded and stable, maintaining the system's safety and responsiveness.

Based on the comparison results between the proposed method and the PID controller, it is evident that under disturbance conditions, the fuzzy controller demonstrates greater robustness. As shown in Figure 7, the tracking performance is more accurate. Figures 8 and 9 also show that the position errors in both the $\boldsymbol{x}$ and $\boldsymbol{y}$ directions are smaller when using the fuzzy controller.

To assess the effectiveness of the proposed method, a comparison with a PID controller is conducted under uncertainties. This comparison demonstrates that the fuzzy controller can achieve better performance in tracking control of mobile robots under disturbances. To quantitatively assess the proposed method against the comparison methods, several performance indices are computed. These indices help to demonstrate the improvement achieved by the proposed method.

Table 1. The performance indices of the system.

	PID controller	Fuzzy controller
ISE_{e_x}	4.315	2.183
IAE_{e_x}	19.741	14.532
RMS_{e_x}	0.106	0.077
ISE_{e_y}	0.546	0.449
IAE_{e_y}	4.900	3.796
RMS_{e_y}	0.037	0.036

According to the performance indices presented in Table 1, all indices related to ISE, IAE, and RMS of the signals e_x and e_y are smaller when using the fuzzy controller compared to the PID controller. Based on these indices, the proposed method demonstrates improved performance under disturbance conditions.

The results confirm that the fuzzy logic controller is capable of delivering high-accuracy trajectory tracking in both ideal and disturbed environments. It provides robustness to disturbances without requiring precise system modeling, which makes it a practical and reliable solution for real-world mobile robot navigation tasks.

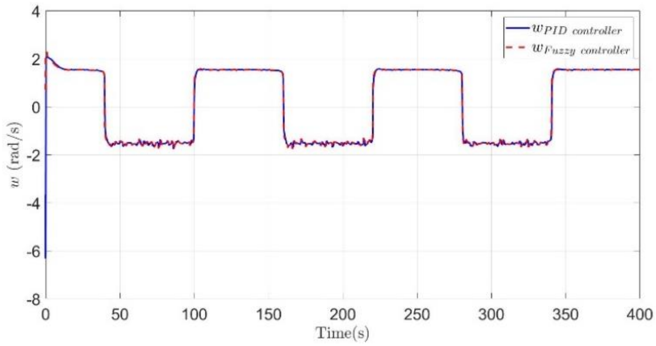

*Figure 11. Control signal **ω** (angular velocity) under disturbance.*

5. CONCLUSION AND FUTURE WORK

In this paper, a fuzzy logic control strategy has been proposed for trajectory tracking of a differential-drive mobile robot. The controller design is based on the Mamdani-type fuzzy inference system, using three parallel fuzzy controllers to independently regulate the robot’s position and orientation errors. Triangular membership functions and a simple rule base were employed to ensure both computational efficiency and interpretability. The simulation results under both nominal and disturbed conditions confirm the effectiveness and robustness of the proposed controller. The robot successfully tracks a predefined sinusoidal trajectory with minimal steady-state error, even in the presence of external disturbances. The control signals remain bounded and smooth, making the method suitable for real-time implementation on embedded platforms. The proposed approach does not rely on an accurate model of the robot dynamics, which highlights one of the key advantages of fuzzy logic control in uncertain and nonlinear environments. However, the performance may still depend on expert-defined membership functions and rules, which can be further optimized.

For future work, the proposed fuzzy logic controller can be extended to more complex scenarios such as multi-robot coordination and obstacle avoidance. Additionally, integrating optimization techniques like Genetic Algorithms or Particle Swarm Optimization may help automate the tuning of membership functions and rule sets, enhancing control performance. Experimental implementation on real mobile robot platforms will be pursued to validate the simulation results. Furthermore, combining fuzzy logic with robust or adaptive control frameworks is a promising direction to improve resilience in highly dynamic and uncertain environments.

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