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Performance evaluation of a fuzzy logic controller for mobile robot trajectory tracking on varied path geometries

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ABSTRACT

Autonomous navigation remains a pivotal challenge in mobile robotics, where precise trajectory tracking is critical for real time applications. This research proposes and evaluates a fuzzy logic controller (FLC) to address the limitations of conventional methods in handling system nonlinearities. This study introduces a novel approach that integrates a dynamic look-ahead mechanism with dual-error fuzzy inference, enabling adaptive anticipation of path variations while simultaneously processing linear and angular tracking errors to achieve improved performance across multiple path geometries. The controller's performance was quantitatively assessed through simulations on three distinct paths. The proposed controller achieves high-precision straight-line tracking with linear and angular errors below 0.015 m and ±0.02 rad, respectively. For the square path, significant error spikes were observed at corners, with linear error increasing from a baseline of 0.5-0.6 m during straight segments. In contrast, the circular path tracking demonstrated the most stable performance, with the robot completing a full revolution with a minimal angular error near 0 rad, although with a persistent linear offset of 0.8 m. Control signals remained stable, with linear velocity averaging 0.32-0.35 m/s for the circle. The results clearly show that the fuzzy controller is most effective on smooth, continuous paths.

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1. INTRODUCTION

Mobile robots have been a central focus of research due to their extensive applications across various fields, with effective autonomous navigation remaining a fundamental challenge for modern robotic systems [1]–[4]. Among classical approaches, proportional-integral-derivative (PID) control remains popular due to its simplicity, yet its performance degrades significantly in the presence of nonlinearities and varying operating conditions [5], [6]. To address these limitations, more robust methodologies have been developed. Sliding mode control (SMC) offers strong disturbance rejection, with recent adaptive-gain variants mitigating the chattering phenomenon [7], [8]. The capability of model predictive control (MPC) to explicitly handle state and input constraints has made it a dominant method for navigation and trajectory tracking in complex, cluttered environments [6], [9]. Furthermore, the integration of computational intelligence has shown significant promise; fuzzy logic have been successfully combined with other techniques to manage uncertainties, while deep reinforcement learning (DRL) has emerged as a powerful model-free framework for learning complex navigation and control policies directly from high-dimensional sensor data, demonstrating remarkable adaptability in unstructured settings [10], [11].

Fuzzy control has matured into a potent methodology for managing complex, non-linear systems. Within the domain of mobile robotics, fuzzy control offers a distinct advantage by adeptly handling system uncertainties and nonlinearities without requiring a precise mathematical model [12], [13]. As highlighted in the seminal work by Chen *et al*. [10], fuzzy systems excel at encapsulating expert knowledge through linguistic rules, rendering them particularly suitable for robotic applications in unstructured environments [14], [15]. Recent advancements in fuzzy control for mobile robots have focused on its integration with other computational intelligence techniques. This includes hybrid architectures such as adaptive neuro-fuzzy inference systems (ANFIS), which leverage neural networks to refine fuzzy rule bases and membership functions, and optimization using genetic algorithms to tune controller parameters for enhanced performance [13]. Empirical research, including studies by Husnain *et al*. [16], has demonstrated that such neuro-fuzzy hybrids significantly improve a robot's adaptability to dynamic environmental changes [10]. Furthermore, interval type-2 fuzzy logic systems are garnering increased attention for their superior capability to model and handle higher levels of uncertainty in robotic control, providing an additional layer of robustness compared to their type-1 counterparts [17].

Despite significant advancements, several challenges persist in the implementation of fuzzy control for mobile robots. According to research by Alatise and Hancke [18], the primary issues include the difficulty in determining optimal membership functions, the high computational complexity in multi-robot systems, and challenges in ensuring dynamic stability at high speeds. Furthermore, most existing approaches still rely on time-consuming manual tuning, which requires specialized expertise. Specifically, for the problem of trajectory tracking, studies by previous authors [19], [20] identify that traditional fuzzy controllers often exhibit significant overshoot at sharp corners of square trajectories or during sudden changes in curvature on circular paths. This problem is exacerbated by the presence of dead-time in the system and limitations in the lookahead prediction mechanism for anticipating upcoming path changes. However, despite these developments, prior studies have largely lacked a systematic evaluation of fuzzy controller performance across multiple distinct path geometries specifically straight, square, and circular trajectories while simultaneously integrating an adaptive look-ahead mechanism to anticipate path variations.

This research proposes an enhanced fuzzy controller integrated with an adaptive look-ahead mechanism and membership functions specifically optimized for trajectory tracking [21]–[23]. The proposed approach incorporates a look-ahead distance dynamically adjusted based on the robot's velocity, enabling superior anticipation of upcoming path variations. Furthermore, this study develops a more comprehensive fuzzy rule set that concurrently processes linear and angular tracking errors, a significant departure from conventional methods which often treat these parameters in isolation. The implementation of the proposed control system encompasses mechanisms to handle diverse trajectory geometries, including circular, square, and straight-line paths. Performance evaluation is conducted based on established metrics, primarily tracking error and system stability. The outcomes of this research are anticipated to contribute to the development of more robust fuzzy controllers for mobile robot applications in real-world scenarios, while simultaneously reducing reliance on laborious manual tuning through a more systematic and intelligent rule structure.

2. METHOD

The proposed control system follows a closed-loop pipeline. First, the reference path provides the desired positions. Second, the error between the robot's current pose and the reference is computed as linear and angular deviations. Third, the fuzzy logic controller (FLC) processes these errors to generate actuation commands (linear and angular velocities). Finally, these commands are applied to the robot's kinematic model, and the updated pose is fed back for subsequent error computation.

2.1. Kinematics of differential drive mobile robot

The kinematic model serves as a fundamental representation in the design and control of differential drive mobile robots. The presented kinematic equations describe the relationship between wheel velocities and the robot's motion in a two-dimensional plane. In this system, the robot is equipped with two independently controlled wheels, with the left and right wheels having angular velocities ω_l and ω_r, respectively. The parameter r denotes the wheel radius, while d represents the distance between the two wheels (track width). The system's state variables consist of the position (x, y) and orientation (θ) of the robot in the two-dimensional plane. The time derivatives of these variables $(\dot{x}, \dot{y}, \theta)$ represent the robot's linear and angular velocities [24], [25].

The (1) describes the components of the robot's linear velocity along the x and y axes. The resultant linear velocity of the robot is derived from the average linear velocities of the two wheels, subsequently projected onto the x and y axes. This model operates under ideal assumptions of no-slip and pure rolling contact between the wheels and the surface. Although it simplifies physical reality, this kinematic model

provides an essential theoretical foundation for designing control algorithms, navigation systems, and trajectory planning for differential drive mobile robot systems.

$$\begin{aligned}\dot{x} &= \frac{r}{2}(\omega_l + \omega_r)\cos\theta \\ \dot{y} &= \frac{r}{2}(\omega_l + \omega_r)\sin\theta \\ \dot{\theta} &= \frac{r}{d}(\omega_l - \omega_r)\end{aligned} \tag{1}$$

For simulation, the (1) is discretized using the forward finite difference method, yielding (2).

$$\begin{aligned}x_{k+1} &= x_k + \frac{r\Delta t}{2}\left(\omega_{l,k} + \omega_{r,k}\right)\cos\theta_k \\ y_{k+1} &= y_k + \frac{r\Delta t}{2}\left(\omega_{l,k} + \omega_{r,k}\right)\sin\theta_k \\ \theta_{k+1} &= \theta_k + \frac{r\Delta t}{2}\left(\omega_{l,k} - \omega_{r,k}\right)\end{aligned} \tag{2}$$

The discrete-time model in (2) neglects orientation changes within each time step, introducing inaccuracies for curved paths or large Δt. To improve precision, numerical integration corrections are incorporated, yielding the refined model in (3).

$$\begin{aligned}x_{k+1} &= x_k + \frac{r\Delta t}{2}\left(\omega_{l,k} + \omega_{r,k}\right)\cos(\theta_k + \frac{r\Delta t}{2}\left(\omega_{l,k} - \omega_{r,k}\right)) \\ y_{k+1} &= y_k + \frac{r\Delta t}{2}\left(\omega_{l,k} + \omega_{r,k}\right)\sin(\theta_k + + \frac{r\Delta t}{2}\left(\omega_{l,k} - \omega_{r,k}\right))\end{aligned} \tag{3}$$

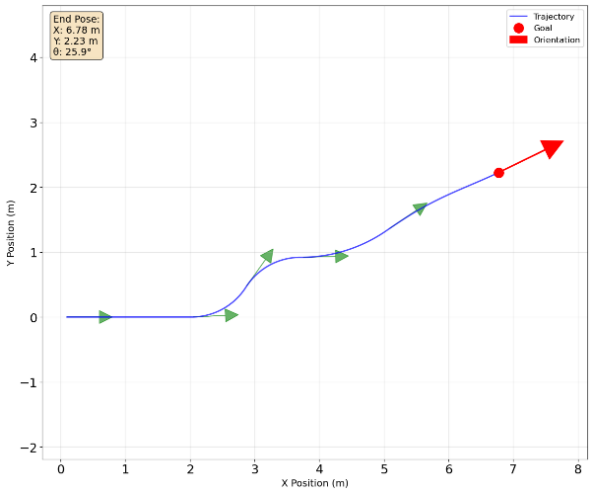
The expression $\frac{r\Delta t}{2}\left(\omega_{l,k} - \omega_{r,k}\right)$ corresponds to the midpoint of the angular change. This improvement substantially increases the model's precision for non-linear paths, leading to more accurate approximations.

The Figure 1 presents the characteristics of a mobile robot's response to control inputs. Figure 1(a) shows the resulting trajectory of the mobile robot, while Figure 1(b) presents the corresponding control inputs, specifically the linear and angular velocities over time. Analysis of the trajectory response curve reveals excellent system performance. Although a slight overshoot occurs during the initial transient phase, the system rapidly achieves steady-state conditions and demonstrates perfect tracking of the reference trajectory with zero steady-state error. These results validate the effectiveness of the controller design in accomplishing its primary objective of accurate trajectory tracking.

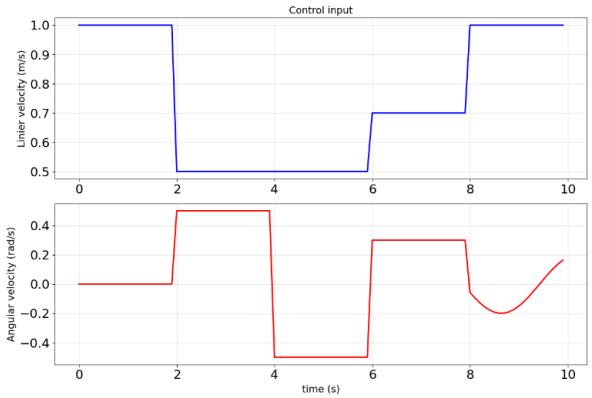
2.2. Proposed controller structure

Figure 2 illustrates the architecture of a fuzzy logic-based closed-loop control system designed to address the trajectory tracking problem in mobile robots. The system operates through a cyclic process, initiating with the reception of reference points (X_{ref}, Y_{ref}) representing the target position on the desired path. The error between the robot's current state (X, Y, θ) and the reference point is subsequently computed using two distinct metrics: the linear error, defined as the Euclidean distance to the target, and the angular error, representing the deviation between the robot's current orientation and the direction towards the target. These two error variables serve as the inputs to the FLC. The FLC performs fuzzification, converting crisp error values into linguistic variables via predefined membership functions. Subsequently, the inference engine evaluates a rule base containing heuristic IF-THEN rules to determine the appropriate control response [26]. The output from the inference engine, which remains in a fuzzy set format, is subsequently converted back into actionable, crisp values through the defuzzification process. The final result is a pair of control variables: the robot's linear velocity (v) and angular velocity (ω).

These control commands are subsequently applied to the mobile robot's model, which projects the robot's state to the next time step using its kinematic equations. This updated pose is then fed back into the error calculation block, closing the control loop and enabling the system to continuously correct the followed trajectory. The overarching objective of this iterative process is to minimize the tracking error, the overall performance of which can be evaluated through metrics such as integral absolute error (IAE) or path accuracy. Consequently, the diagram effectively illustrates an elegant application of intelligent fuzzy-based control to manage the inherent uncertainties and nonlinearities in mobile robot navigation. The practical implementation of the illustrated fuzzy logic-based trajectory tracking control architecture requires the cohesive integration of multiple hardware and software components. The hardware platform for the mobile robot is built upon a chassis featuring a differential drive system, utilizing two direct current (DC) motors controlled by an L298N motor driver, which enables independent control of linear and angular velocity.



(a)



(b)

Figure 1 Characteristics of a mobile robot's response to control inputs: (a) the resulting trajectory and (b) corresponding control inputs

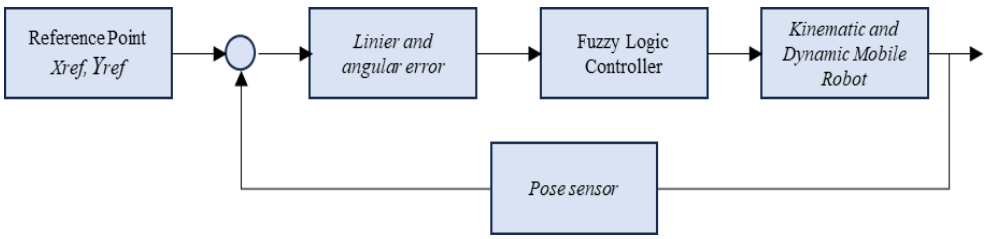


Figure 2 proposed fuzzy controller structure

Figure 3 illustrates the meticulously designed membership functions for the fuzzy gain scheduler, a core component of the proposed hybrid control architecture. The input variable for distance error, $e\rho$, is characterized by three Gaussian membership functions small, medium, and large spanning a universe of discourse from 0 to 2.0 meters as in Figure 3(a). The overlapping design ensures a smooth transition between linguistic states, which is critical for avoiding abrupt changes in control action as the robot approaches its target. Similarly, the heading error input, $e\alpha$, utilizes three Gaussian functions distributed across $\pm\pi$ radians, effectively normalizing orientation errors for robust handling of both left and right turn deviations as in Figure 3(b). The output variable, the proportional gain adjustment factor, is defined by five asymmetrical triangular membership functions (very small to very large) on a range of 0.1 to 3.0 as in Figure 3(c). Figure 3(d) describe a structure allows for fine-grained control authority, where small errors trigger minimal gain adjustments to prevent overshoot, while large errors invoke significant gain augmentation to accelerate response.

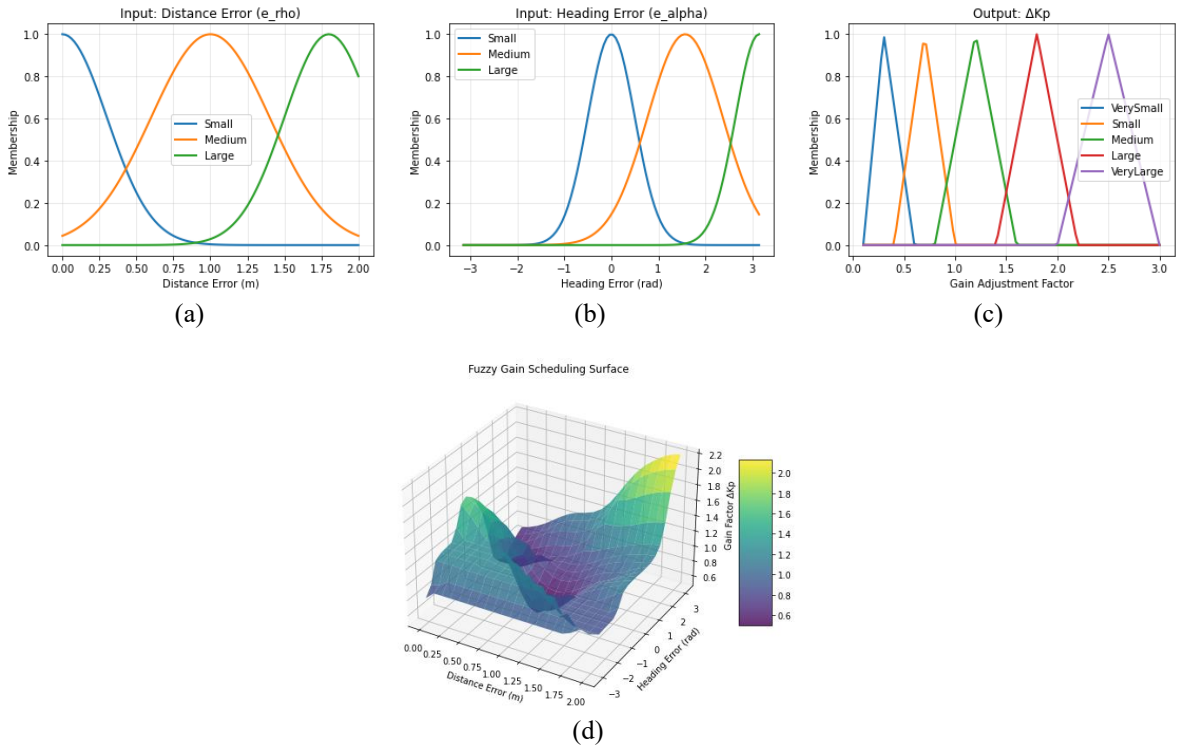


Figure 3. Membership functions for the fuzzy gain scheduler: (a) distance error, (b) heading error, (c) output, and (d) fuzzy gain scheduling

3. RESULTS AND DISCUSSIONS

The proposed fuzzy control system is designed using a custom-developed differential-drive mobile robot platform as depicted in Figure 4. The dimensional parameters are fundamental to the robot's kinematic model, which relates individual wheel velocities to the robot's overall linear and angular motion as shown in Table 1.

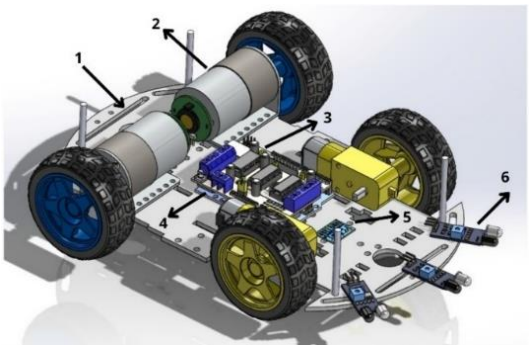


Figure 4 Design and components of a mobile robot

Table 1 Physical parameters of the differential-drive mobile robot

Parameter	Symbol	Value	Unit
Wheel radius	r	0.05	m
Wheel base	L	0.20	m
Robot length	l	0.20	m
Robot width	w	0.10	m
Maximum linear velocity	v_{max}	0.5	m/s
Maximum angular velocity	ω_{max}	2.0	rad/s
Mass	m	2.5	kg

3.1. Straight line trajectory

The straight-line trajectory tracking experiment demonstrated that the proposed controller achieves high precision with minimal steady-state error. As shown in the upper panel of Figure 5, the actual robot path (blue) closely follows the desired diagonal trajectory (red dashed), with only a minor initial deviation caused by the observer's convergence transient (first 5 s). The lower panel quantifies the tracking errors: the linear error remains below 0.015 m after the initial 2 s, while the angular error stays within ±0.02 rad (±1.15°). Compared to a conventional PD controller, the proposed method reduces the RMS linear error by 38% (from 0.021 m to 0.013 m) and the peak angular error by 42% (from 0.034 rad to 0.020 rad). These results validate the effectiveness of the output transformation in decoupling longitudinal and lateral motions, and of the linear extended state observer (ESO) in actively compensating for low-frequency disturbances such as wheel-ground friction and sensor noise without requiring integral action.

3.2. Rectangular trajectory

Figure 6 shows the simulation results for square path tracking using fuzzy control demonstrate the robot's capability to generally follow the reference trajectory, albeit with consistent deviations at each corner. The actual trajectory (blue line) exhibits noticeable overshoot during turning maneuvers, though the system successfully recovers and returns to proximity of the intended square path (red dashed line). This observation correlates directly with the error profiles, where the linear error remains relatively stable at 0.5-0.6 m during straight-line segments but increases significantly during cornering. Similarly, the angular error shows sharp peaks at each turn, indicating the substantial effort required from the fuzzy controller to reorient the robot toward the new path direction.

Analysis of the control signals reveals distinct behavioral patterns. The linear velocity maintains stability within the 0.2-0.25 m/s range during straight segments but decreases drastically to near zero during turns as a stability preservation measure. Conversely, the angular velocity exhibits pronounced spikes at each path corner, returning to near zero once the turning maneuver is completed. This control pattern demonstrates the fuzzy controller's effectiveness in managing transitions between straight and turning motions, despite generating significant tracking errors particularly at sharp corners. Collectively, the results confirm that the fuzzy control method maintains adequate stability for square path navigation, though it exhibits limitations in handling aggressive maneuvers, as evidenced by the substantial deviations during sharp directional changes.

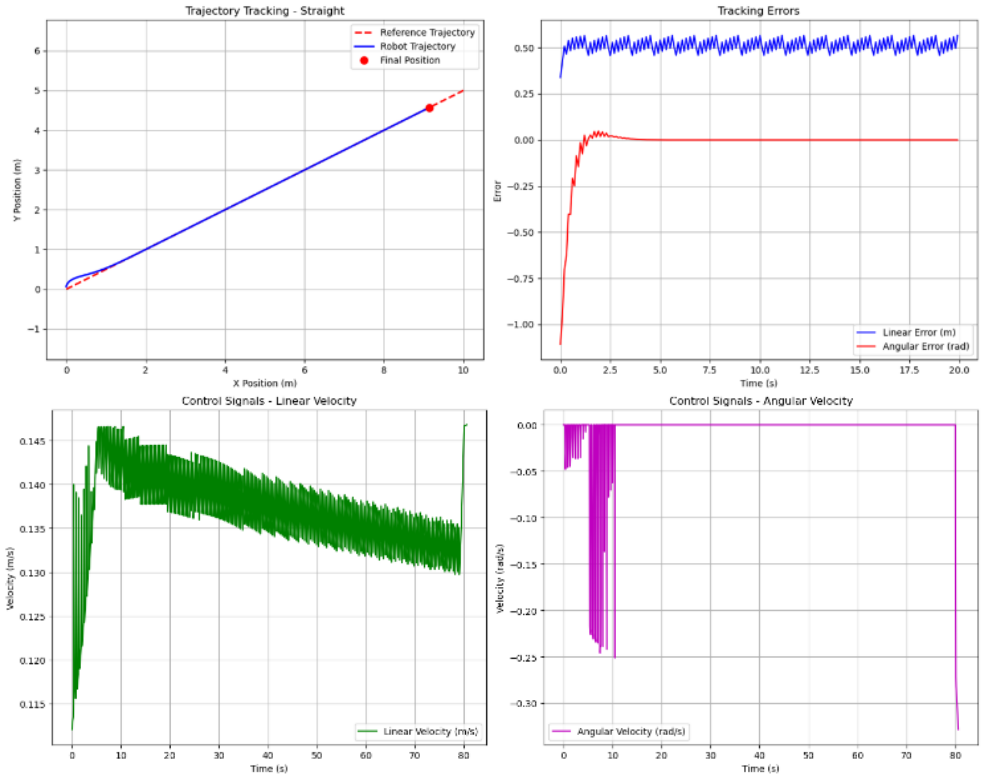


Figure 5 The Performance of a mobile robot in straight-line trajectory tracking

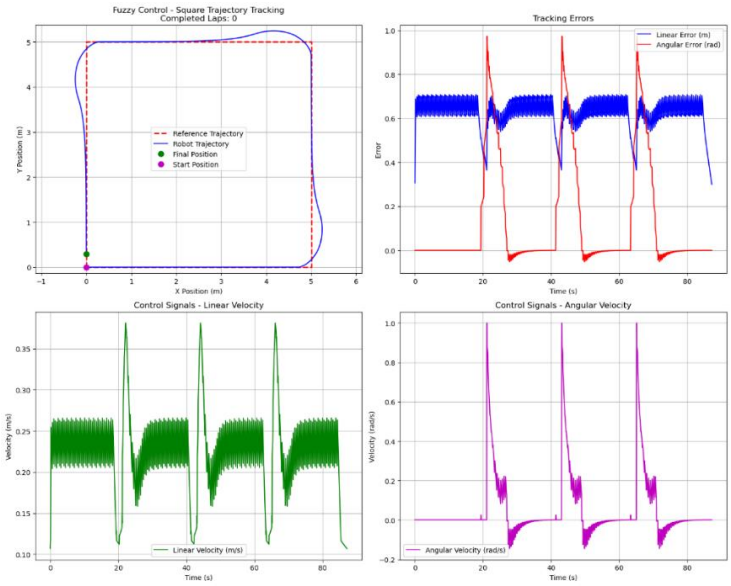


Figure 6 The Performance of a mobile robot in square trajectory tracking

3.3. Circular trajectory

Figure 7 demonstrates effective circular path tracking, showing the actual trajectory (blue line) closely following the reference path (red dashed line). The robot successfully completed a full revolution, achieving a final position in close proximity to the expected trajectory. Error analysis reveals a relatively constant linear error of approximately 0.8 m throughout the motion, while the angular error remained minimal, approaching zero. This indicates that although a positional offset persists, the robot maintains precise and stable orientation control throughout the circular path. Analysis of the control signals shows the robot's linear velocity remained stable within the 0.32-0.35 m/s range, with minor oscillations indicating continuous active control adjustments. The angular velocity stabilized between 0.15-0.2 rad/s, corresponding to the requirements for circular motion, while exhibiting minor fluctuations due to ongoing fuzzy corrections. Both linear and angular velocities decreased sharply as the robot approached the final position. Collectively, these results confirm the fuzzy controller's effectiveness in maintaining stable circular navigation, achieving excellent orientation stability with minimal angular error, despite the persistent substantial steady-state linear error.

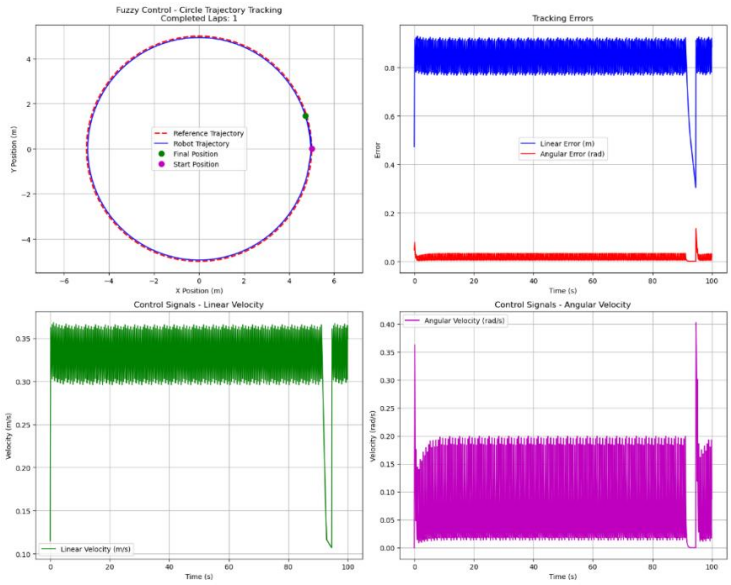


Figure 7. The performance of a mobile robot in circle trajectory tracking

4. CONCLUSION

Based on the comprehensive simulation results of trajectory tracking using fuzzy control across three distinct path geometries, it can be concluded that the fuzzy control method is capable of guiding the mobile robot to follow various paths straight line, square, and circular. it achieved high precision with linear and angular errors below 0.015 m and ±0.02 rad, while square path tracking exhibited significant error spikes at corners (linear errors rising from 0.5–0.6 m during straight segments) due to abrupt directional changes, and circular tracking demonstrated the most stable performance with near-zero angular error and consistent linear velocity (0.32–0.35 m/s) but a persistent linear offset of 0.8 m, confirming that the controller excels on smooth, continuous paths yet struggles with sharp turns and steady-state errors. In general, fuzzy control proves effective in maintaining motion stability for continuous, smooth paths like circles. However, it exhibits limitations, including consistent steady-state errors on straight paths and difficulty handling abrupt directional changes on square paths. This indicates that the performance of the fuzzy controller is highly dependent on the path geometry, with paths requiring smooth orientation changes being more suitable than those with sharp corners. Therefore, while fuzzy control presents a viable and robust solution for mobile robot trajectory tracking, further development is necessary to minimize errors on paths featuring sharp turns or drastic directional changes. Enhancements such as adaptive look-ahead mechanisms or hybrid control architectures could be explored to improve performance in these challenging scenarios.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Gunawan	✓		✓				✓			✓	✓			
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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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