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Experimental Comparison of Classical, Fractional-Order, and Fuzzy Controllers for Trajectory Tracking †

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Abstract

This paper experimentally compares PI, TI, FOPI, and Fuzzy-PI controllers for trajectory tracking of a Festo Robotino under identical conditions using square, circular, and lemniscate trajectories. Performance is evaluated using ISE, IAE, and ISU. Fuzzy-PI provides the most consistent Cartesian tracking, particularly under abrupt or alternating direction changes, while PI remains competitive in orientation control with lower effort. The results confirm a trade-off between tracking accuracy and control effort.

Keywords: omnidirectional mobile robot; trajectory tracking; fractional-order control; fuzzy control; mobile robot control

1. Introduction

Mobile robotics has experienced significant growth in recent years, becoming an essential component of modern automation systems with applications in manufacturing, logistics, inspection, transportation, and service robotics [1]. Among the different platforms, omnidirectional mobile robots are particularly attractive due to their ability to perform simultaneous translational and rotational motions, enabling high maneuverability and precise positioning in confined environments [2,3].

Despite these advantages, accurate trajectory tracking remains challenging due to nonlinear robot dynamics, with coupling among motion variables, actuator limitations, model uncertainties, odometry errors, and external disturbances. These factors can significantly affect both tracking accuracy and control effort, especially when the robot follows trajectories with different geometric characteristics [4]. Several control strategies have been proposed to address these challenges. Conventional proportional–integral (PI) controllers remain attractive because of their simplicity, whereas Tilt–Integral (TI) and fractional-order proportional–integral (FOPI) controllers provide additional tuning flexibility. Similarly, Fuzzy-PI controllers improve adaptability under nonlinear operating conditions. Experimental studies have demonstrated the potential of these approaches for trajectory tracking [4–6]; however, direct comparisons remain difficult because different robotic platforms, trajectories, tuning procedures, and performance criteria are typically used.

Therefore, this paper presents an experimental comparison of PI, TI, FOPI, and Fuzzy-PI controllers using a Festo Robotino under identical operating conditions. Square, circular, and lemniscate trajectories are considered to represent different tracking scenarios, while

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performance is quantified using the Integral of Squared Error (ISE), Integral of Absolute Error (IAE), and Integral of Squared Control Effort (ISU), allowing the trade-off between tracking accuracy and control effort to be systematically assessed.

2. Robotino Platform Description

The Festo Robotino is a three-wheeled omnidirectional mobile robot designed for research and educational applications [3]. Its locomotion system consists of three independently driven omnidirectional wheels symmetrically arranged at 120° intervals, as shown in Figure 1. The passive rollers allow for lateral motion, allowing simultaneous translation and rotation in the plane.

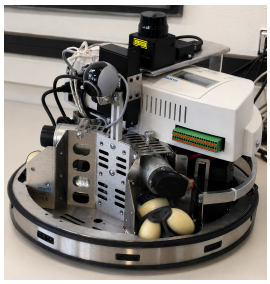


Figure 1. Festo Robotino used in the experiments.

The robot pose in the global reference frame is defined as $\mathbf{q}(t) = [x(t),\, y(t),\, \phi(t)]^T$, where $x(t)$ and $y(t)$ denote the Cartesian position and $\phi(t)$ the orientation. The kinematic model relates the wheel velocities to the robot velocity as

$$\dot{\mathbf{q}}(t) = \mathbf{J}(\phi(t))\mathbf{v}(t), \qquad \mathbf{v}(t) = \begin{bmatrix} v_1(t) & v_2(t) & v_3(t) \end{bmatrix}^T, \tag{1}$$

where $\mathbf{J}(\phi(t))$ is the configuration-dependent Jacobian determined by the robot orientation and geometric parameters. In the experimental implementation, the OmniDrive block performs the inverse kinematic transformation from Cartesian control commands to wheel velocity references.

3. Controller Design

Let the tracking error for each controlled coordinate be defined as

$$e_j(t) = q_{j,r}(t) - q_j(t), \qquad j \in \{x, y, \phi\}, \tag{2}$$

where $q_{j,r}(t)$ and $q_j(t)$ denote the reference and measured coordinates, respectively. The controllers are applied independently to the three controlled coordinates.

3.1. PI Controller

The PI controller used as the conventional baseline is defined as

$$C_{\mathrm{PI}}(s) = K_p + \frac{K_i}{s}, \tag{3}$$

where K_p and K_i are the proportional and integral gains, respectively.

3.2. TI Controller

The Tilt-Integral (TI) controller replaces the proportional action with the fractional-order tilt operator $s^{-1/n}$ [7]. The implemented controller is

$$C_{\mathrm{TI}}(s) = \frac{K_t}{s^{1/n}} + \frac{K_i}{s}, \qquad n > 0, \tag{4}$$

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where K_t, K_i, and n denote the tilt gain, the integral gain, and the tilt-order parameter, respectively.

3.3. FOPI Controller

The Fractional-Order PI (FOPI) controller generalizes the conventional PI by introducing a fractional integration order:

$$C_{\mathrm{FOPI}}(s) = K_p + \frac{K_i}{s^{\lambda}}, \qquad \lambda > 0. \tag{5}$$

The conventional PI is recovered for $\lambda = 1$, while λ provides an additional degree of freedom to shape the closed-loop response [8,9]. For practical implementation, the fractional-order terms in the TI and FOPI controllers were implemented in MATLAB/Simulink 2025a using the FOMCON toolbox, which employs finite-dimensional rational approximations based on the Oustaloup recursive approximation [9]. Thus, $s^{-1/n}$ and $s^{-\lambda}$ are realized as conventional rational filters.

3.4. Fuzzy-PI Controller

A gain-scheduled Fuzzy-PI controller is employed to improve adaptation to nonlinear and uncertain behavior [5]. For each controlled coordinate, the control law is the following:

$$u_j(t) = K^*_{p,j}(t) e_j(t) + K^*_{i,j}(t) \int_0^t e_j(\tau)\, d\tau, \tag{6}$$

where the effective gains are adjusted online as

$$K^*_{p,j}(t) = K_{p,j} + \Delta K_{p,j}(t), \qquad K^*_{i,j}(t) = K_{i,j} + \Delta K_{i,j}(t). \tag{7}$$

A Mamdani inference system determines $\Delta K_{p,j}(t)$ and $\Delta K_{i,j}(t)$ from the tracking error $e_j(t)$ and the accumulated error $E_j(t) = \int_0^t e_j(\tau)\, d\tau$.

3.5. Orientation Error

Due to the periodicity of the orientation, the angular tracking error is wrapped to $[-\pi, \pi]$:

$$e_{\phi}(t) = \mathrm{atan2}[\sin(\phi_r(t) - \phi(t)), \cos(\phi_r(t) - \phi(t))]. \tag{8}$$

This definition ensures correction along the shortest angular displacement.

4. Results and Discussion

The PI, TI, FOPI, and Fuzzy-PI controllers were experimentally evaluated using square, circular, and lemniscate trajectories, representing abrupt direction changes, continuous curvature, and alternating curvature, respectively. Performance was assessed through trajectory tracking, error evolution, control actions, and the ISE, IAE, and ISU indices.

4.1. Tuning Parameters

All controllers were evaluated under identical experimental conditions. The PI gains were initialized using the Dahlin method and experimentally refined using ISE as the main criterion, see Table 1. These settings were used as initial references for TI and FOPI, whose parameters were subsequently adjusted using the same criterion. Since $K_t/s^{1/n}$ is dynamically different from a proportional term, identical K_t and K_p values were not imposed.

Table 1. Controller parameters.

Controller	Axis	K_p/K_t	K_i	Parameter
PI	X, Y	3.0	0.010	–
	ϕ	2.8	0.010	–
TI	X, Y	3.0	0.001	$n = 5$
	ϕ	2.5	0.001	$n = 5$
FOPI	X, Y	4.0	0.010	$\lambda = 0.9$
	ϕ	3.8	0.010	$\lambda = 0.9$

A Mamdani-type fuzzy controller with two inputs (e_p and e_i) and one output (u) was implemented. The same membership functions and symmetric 15-rule IF–THEN rule base were used for the X-, Y-, and ϕ-axes, providing consistent control behavior for all motion variables.

4.2. Square Trajectory

Figure 2 shows the experimental tracking of the square reference. The abrupt direction changes at the corners produce the largest deviations, with Fuzzy-PI following the reference more closely, particularly during these transitions.

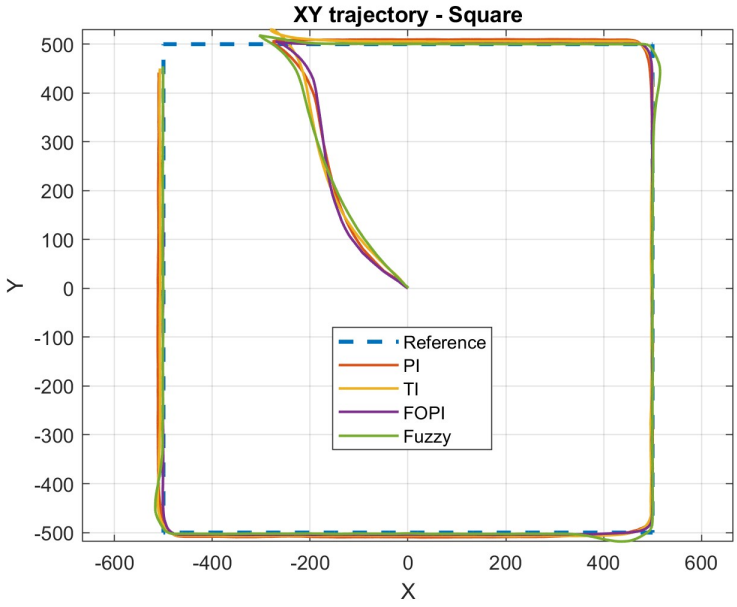
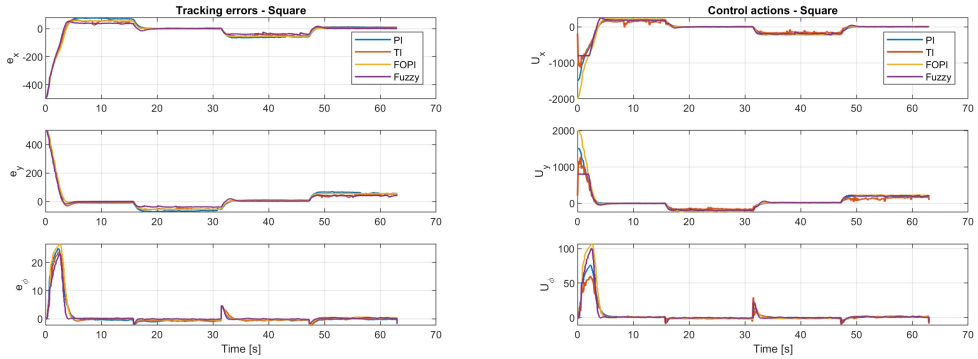


Figure 2. Experimental tracking of the square trajectory.

The error and control evolutions in Figure 3 show that the largest variations occur during the initial transient and at the corners. After each transition, the errors decrease and remain bounded. FOPI exhibits higher control activity in some intervals, whereas Fuzzy-PI achieves faster Cartesian error recovery with comparatively moderate actuation.

The performance indices in Figure 4 confirm these observations. Fuzzy-PI achieves the lowest translational ISE and IAE, reducing IAE_x from 2855.8 with PI to 1937.4, which corresponds to approximately 32%. FOPI presents the highest translational control effort, with ISU values of 5.74×10^6 and 6.68×10^6 for X and Y, respectively, compared with 2.66×10^6 and 2.65×10^6 for Fuzzy-PI.



(**a**) Tracking errors. (**b**) Control actions.

Figure 3. Experimental response for the square trajectory: (**a**) tracking errors and (**b**) control actions.

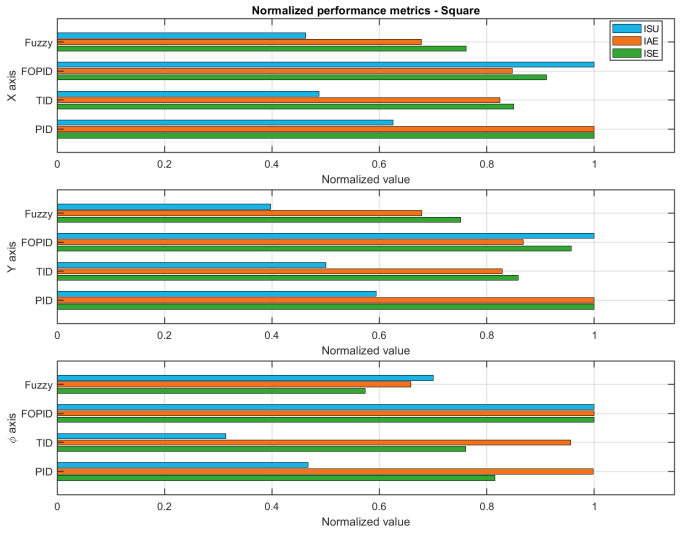


Figure 4. Normalized performance indices for the square trajectory.

4.3. Circular Trajectory

Figure 5 shows that all controllers reproduce the circular reference, with smaller differences than for the square trajectory due to its continuous curvature. Fuzzy-PI provides the closest overall tracking in the Cartesian plane.

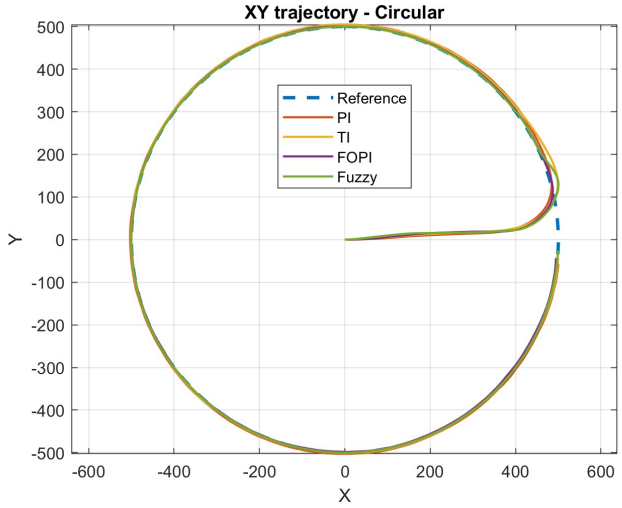
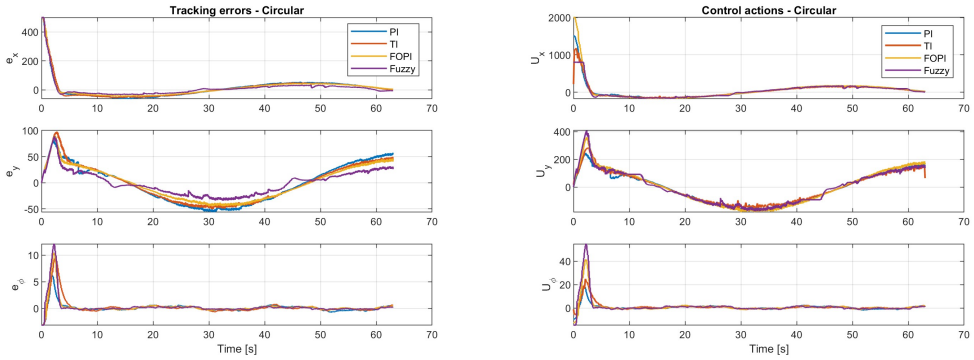


Figure 5. Experimental tracking of the circular trajectory.

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As shown in Figure 6, the tracking errors exhibit an initial transient and subsequently remain bounded, while the control actions become smoother as the robot follows the continuous-curvature reference.



(**a**) Tracking errors. (**b**) Control actions.

Figure 6. Experimental response for the circular trajectory: (**a**) tracking errors and (**b**) control actions.

The quantitative results in Figure 7 reveal a trade-off between tracking accuracy and control effort. Fuzzy-PI achieves the lowest translational indices, with $ISE_x = 2.73 \times 10^5$ and $IAE_x = 1861.7$. In contrast, PI achieves the lowest orientation ISE and ISU, with $ISE_\phi = 45.063$ and $ISU_\phi = 413.38$. Thus, Fuzzy-PI provides superior Cartesian tracking, whereas PI requires lower accumulated angular control effort.

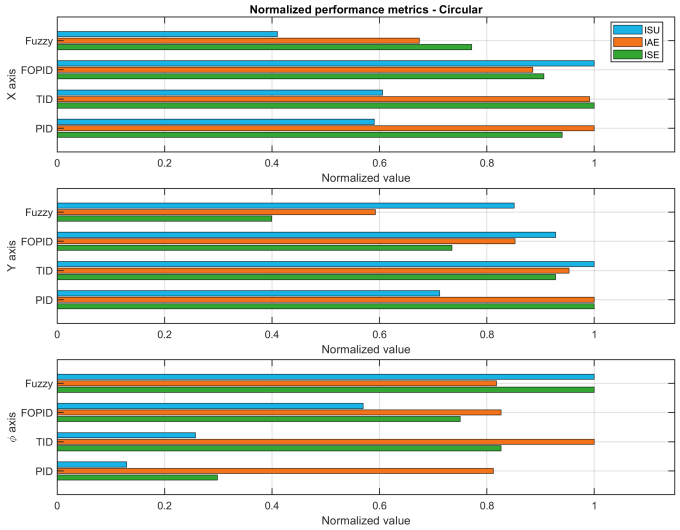


Figure 7. Normalized performance indices for the circular trajectory.

4.4. Lemniscate Trajectory

The lemniscate combines alternating curvature with a central crossing, requiring coordinated corrections in both Cartesian directions. Figure 8 shows that all controllers reproduce the reference shape, while Fuzzy-PI provides the closest overall spatial tracking.

Figure 9 shows that the tracking errors and control actions vary with the alternating curvature. The errors remain bounded throughout the experiment, with Fuzzy-PI exhibiting lower Cartesian errors, while FOPI requires greater corrective activity in some intervals.

The performance indices in Figure 10 show that Fuzzy-PI achieves the lowest accumulated tracking errors, including $ISE_\phi = 39.165$ and $IAE_\phi = 18.867$. However, PI obtains the lowest angular control effort, with $ISU_\phi = 556.54$. This result again demonstrates that improved tracking accuracy does not necessarily correspond to minimum actuation demand.

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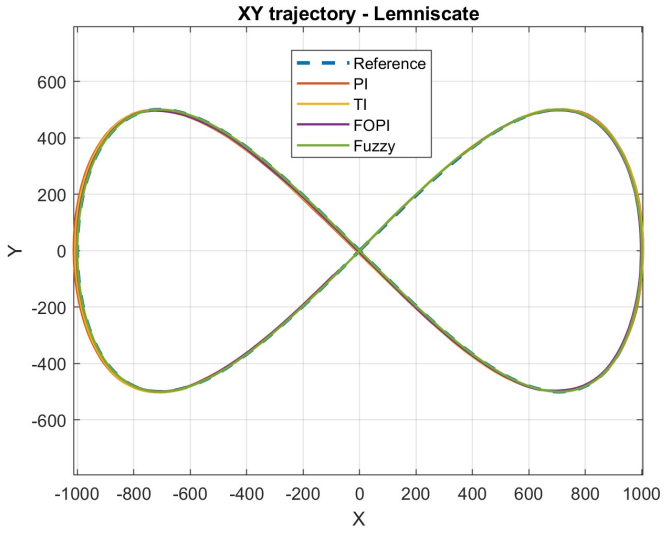
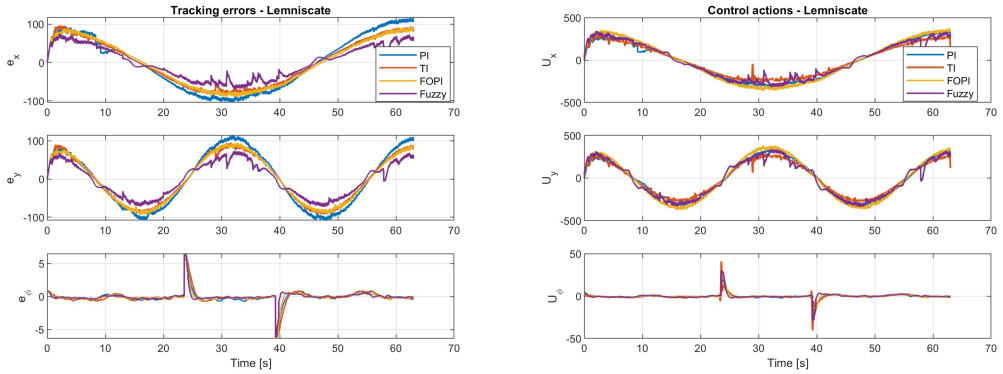


Figure 8. Experimental tracking of the lemniscate trajectory.



(**a**) Tracking errors. (**b**) Control actions.

Figure 9. Experimental response for the lemniscate trajectory: (**a**) tracking errors and (**b**) control actions.

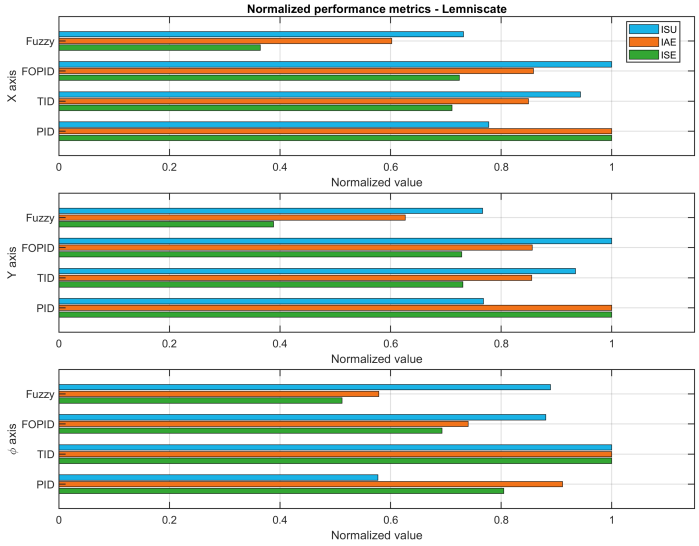


Figure 10. Normalized performance indices for the lemniscate trajectory.

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4.5. Comparative Discussion

The experiments show that controller performance depends on both trajectory geometry and the controlled degree of freedom. Fuzzy-PI provides the most consistent Cartesian tracking, particularly under abrupt direction changes, while PI remains competitive in orientation control with lower angular effort in some cases. FOPI generally requires greater actuation effort, whereas TI provides an intermediate compromise. Overall, no controller minimizes all performance indices, confirming the trade-off between tracking accuracy and control effort.

5. Conclusions

This paper experimentally compares PI, TI, FOPI, and Fuzzy-PI controllers for Robotino trajectory tracking. Fuzzy-PI provided the most consistent Cartesian tracking, while PI remained competitive in orientation control with lower effort in some cases, confirming a trade-off between tracking accuracy and actuation demand. Dedicated disturbance rejection tests were not included because the current setup does not provide controlled and repeatable external perturbations; this aspect remains for future work.

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