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Hybrid Intelligent Control for a Transradial Prosthetic Wrist Using PID, Fuzzy Logic, and Particle Swarm Optimization

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Abstract. This study presents the development of a hybrid intelligent control system for a transradial prosthetic wrist, integrating Proportional-Integral-Derivative (PID) control, Fuzzy Logic, and Particle Swarm Optimization (PSO). The prosthesis, designed by Labbio, incorporates a motor, harmonic reducer, and magnetorheological (MR) brake to enable precise torque control. Three distinct operation scenarios were considered: abrupt motion, smooth high-precision movement, and a hybrid mode alternating between both. A mathematical model of the wrist mechanism was formulated, relating motor and brake electrical inputs to the output torque while respecting mechanical constraints. For each scenario, torque reference curves were defined, and PID parameters were automatically optimized using PSO. To enable real-time adaptability, a Fuzzy Logic system dynamically selects the most appropriate PID gains based on the movement regime. Simulation results demonstrate that the hybrid control system achieves stable and responsive performance across all scenarios. The Fuzzy-PSO-PID approach enables smooth transitions between motion types, reducing overshoot and delay while enhancing precision and user comfort. This work highlights the potential of combining classical control, soft computing, and bio-inspired optimization techniques to address nonlinear and time-varying challenges in biomedical prosthetic applications.

Keywords: Prosthetic wrist, Intelligent control, Particle Swarm Optimization (PSO), Fuzzy logic, Magnetorheological (MR).

1 Introduction

The growing demand for advanced upper limb prostheses has driven research towards improving user functionality and comfort. Transradial prosthetic wrists play a fundamental role in enhancing the range of motion and user dexterity in daily tasks. However, current commercial prosthetic wrists remain limited in torque capacity, control flexibility, and adaptability to different task demands [1], [2]. To address these limitations, this study presents the development of a hybrid intelligent control system for a transradial prosthetic wrist. The system integrates Proportional-Integral-Derivative (PID) control, Fuzzy Logic, and Particle Swarm Optimization (PSO) techniques. This integration enables dynamic adaptation of control parameters in real time, according to different operational scenarios such as abrupt motion, precision movement, and hybrid transitions between modes [3], [4]. The prosthesis, developed by Labbio, includes a motor, a harmonic drive reducer, and a magnetorheological (MR) brake. This configuration allows both active and resistive torque control with high responsiveness and accuracy [5], [6]. Previous works have shown the potential of combining intelligent control techniques to enhance performance in nonlinear and time-varying systems [7]. However, few studies have applied such hybrid control strategies in biomedical devices, particularly in prosthetic wrists [8], [9]. This paper details the mathematical modeling, controller design, optimization process, and simulation results of the proposed system.

2 Methodology

The study follows a multi-step methodology combining mechanical modeling, control system design, and numerical simulation.

2.1 System Modeling

The rotational dynamics of the prosthetic wrist system, composed of a motor, harmonic drive, and MR brake, can be described by the rotational form of Newton's second law [10]:

$$J_{eq}\frac{d^2\theta(t)}{dt^2} + b\frac{d\theta(t)}{dt} = \tau_{motor}(t) - \tau_{brake}(t). \quad (1)$$

Where J_{eq} is the equivalent rotational inertia, b Is the equivalent damping coefficient, $\tau_{\mathrm{motor}}(\mathrm{t})$ is the motor unit torque, composed of motor and reducer, $\tau_{\mathrm{brake}}(\mathrm{t})$ is the resistive torque generated by the MR brake, and $\theta(\mathrm{t})$ is the angular position of the joint over time. The transradial prosthetic wrist being studied is shown in Fig. 1, adapted from [11].

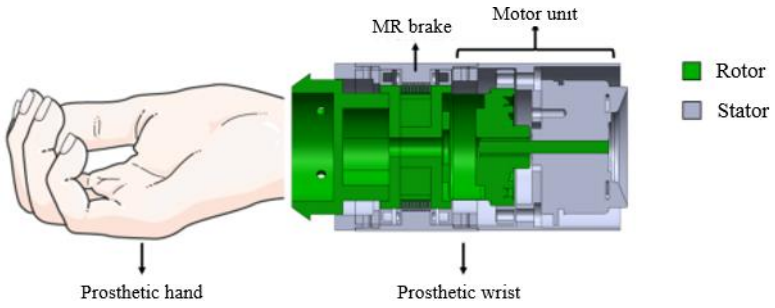


Figure 1. Cross-sectional view of the wrist prosthesis with MR brake

The MR brake torque was modeled based on the Bingham plastic model [12],[13],[14],[15], as expressed as:

$$T = 2N\pi\left[\frac{\tau_y}{3}(r_0^3 - r_i^3) + \frac{\omega\mu_{MR}}{4h}(r_0^4 - r_i^4)\right]. \quad (2)$$

Where N is the number of active shear gaps, τ_y is the yield stress of the MR fluid (function of magnetic field intensity), r_o, r_i are the outer and inner disk radius, h is the gap thickness, μ_{MR} is the viscous damping coefficient and ω is the angular velocity. The values used were based on the prosthesis designed by Labbio. Parameters such as MR yield stress (τ_y), viscosity (μ_{MR}), and gap (h) were selected based on typical values reported in the literature for MR brakes in prosthetic applications. Studies [14], [12], provide representative ranges of yield stress and viscosity, which were consistent with the 4.87 N·m brake torque limit adopted in this work.

2.2 System Control

The PID controller output $u(t)$ is computed as:

$$u(t) = K_p e(t) + K_i\int_0^T e(t)dt + K_d\frac{de(t)}{dt}. \quad (3)$$

Where T is the total simulation time, $e(t)$ is the tracking error between desired and actual torque, u is the control signal, parameters Kp, Ki and Kd are the proportional gain, integral gain, and derivative gain, respectively. The controller performance was evaluated using four error indices [16]:

Integral Squared Error (ISE):

$$ISE = \int_0^T e^2(t)dt. \quad (4)$$

Integral Absolute Error (IAE):

$$IAE = \int_0^T |e(t)|dt. \tag{5}$$

Integral Time Absolute Error (ITAE):

$$ITAE = \int_0^T t|e(t)|dt. \tag{6}$$

Integral Squared Time Error (ISTE):

$$ISTE = \int_0^T t^2 e^2(t)dt. \tag{7}$$

The PID controller included anti-windup protection implemented through back-calculation, with saturation handled by clamping at actuator torque limits.

The Particle Swarm Optimization (PSO) algorithm was employed to tune PID gains for each scenario [17]. The PSO position and velocity update rules are:

$$v_i(t+1) = wv_i(t) + c_1 r_1 \left(pbest_i - x_i(t)\right) + c_2 r_2 (gbest - x_i(t)). \tag{8}$$

$$x_i(t+1) = x_i(t) + v_i(t+1). \tag{9}$$

Where x_i is the position of particle i (PID gains), v_i is the velocity of particle i, w is the inertia weight, c_1, c_2 are cognitive and social acceleration coefficients, r_1, r_2 are random numbers uniformly distributed in [0,1], $\mathrm{pbest_i}$ is the personal best particle i and gbest is the global best found so far. The Parameters of PSO-PID tuning method used is shown in Tab. 1. Stability screening discarded unstable or oscillatory responses. Gains were constrained within practical ranges of 0 to 0.1, for the input electrical current, based on preliminary tests. The inertia weight w was fixed at 0.9 for convergence consistency.

Table 1. Parameters of PSO-PID tuning method

Parameter	Symbol	Value
Population size	M	20
Number of iterations	N_i	200
Inertia weight range	$[w_{min}, w_{max}]$	0.9
Cognitive parameter	c_1	2.0
Social parameter	c_2	2.0

A Fuzzy Logic system was implemented to enable real-time switching between PID parameter sets optimized for each scenario. The fuzzy input variables were based on the magnitude and rate of change of the desired torque. Output variables determined the appropriate PID parameter set.

Simulations were conducted using Python to evaluate performance across several reference trajectories: abrupt motion, abrupt motion with braking, and precision movement. These were represented by step, resistive step, and sinusoidal curves, respectively. Performance was assessed based on the error criteria outlined earlier. For the step and resistive step reference trajectories, an amplitude of 4.5 N·m was chosen, as this is below the maximum brake torque limit of 4.87 N·m, limited by the actuator capacity. For the sinusoidal reference trajectories, an amplitude of 1.5 N·m was used, which corresponds to the typical torque required for daily basic activities [18]. A sampling rate of 100 Hz with an integration step of 10 ms was used. The motor response delay was set to 200 ms and the brake to 112 ms [11].

3 Results and Discussion

3.1 PID Optimization with Different Error Criteria

PID controllers were optimized for each scenario using four different error criteria: ISE, IAE, ITAE, and ISTE. In the scenarios step, resistive step and sinusoidal torque input as respectively shown in Fig. 2, 3 and 4. For the abrupt torque application scenario, controllers optimized with IAE showed the lowest absolute error values while maintaining acceptable overshoot, outperforming other criteria (Tab. 2). Similarly, for the resistive step scenario (Tab. 3), IAE-based optimization provided better transient response and lower overshoot. In the sinusoidal

(Tab. 4) tracking case, the IAE-tuned controller exhibited superior tracking performance and smoother response. These findings align with previous studies emphasize the robustness and balanced performance of IAE in systems with multiple performance requirements [19].

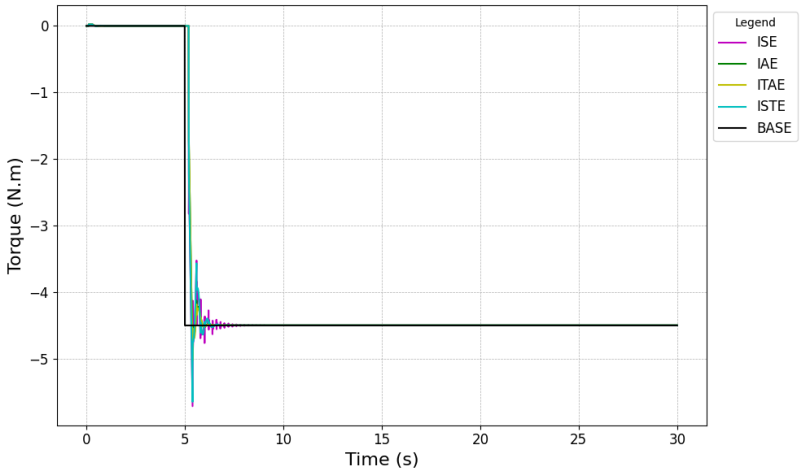


Figure 2. Result in the step scenario with different error criteria

Table 2. Performance indices for each optimization criterion (step torque input)

Error Criteria	ISE	IAE	ITAE	ISTE	Overshoot	Peak overshoot	Rise time (s)	Settling time (s)	Steady state error
ISE	438.27	133.54	754.46	11466.80	0.21	0.27	0.10	6.41	0.0020
IAE	451.91	128.51	726.26	11812.47	0.10	0.11	0.14	5.83	0.0021
ITAE	452.36	128.59	725.58	11823.81	0.10	0.12	0.14	5.83	0.0021
ISTE	440.68	133.25	752.53	11530.21	0.20	0.25	0.11	6.16	0.0020

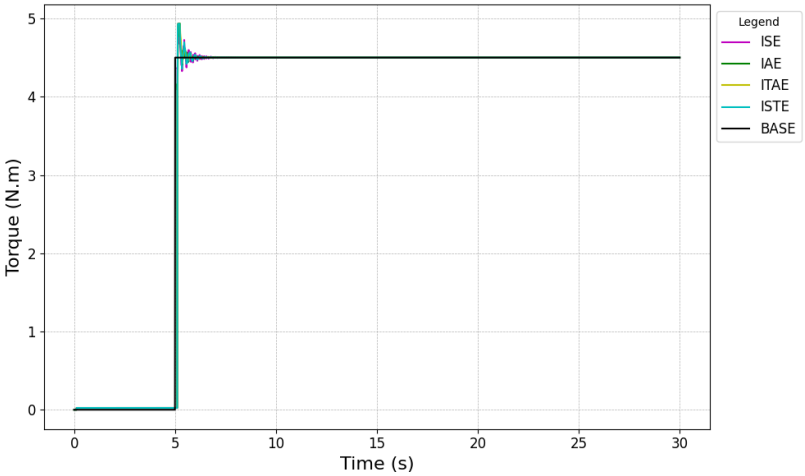


Figure 3. Result in the resistive step scenario with different error criteria

Table 3. Performance indices for each optimization criterion (resistive step torque input)

Error Criteria	ISE	IAE	ITAE	ISTE	Overshoot	Peak overshoot	Rise time (s)	Settling time (s)	Steady state error
ISE	222.94	72.11	369.63	5686.16	0.09	0.10	0.00	5.68	0.0010
IAE	223.20	71.37	364.65	5692.54	0.09	0.10	0.00	5.47	0.0010

ITAE	223.85	72.25	369.04	5709.96	0.09	0.10	0.01	5.51	0.0010
ISTE	223.35	73.06	374.20	5697.33	0.09	0.10	0.00	5.51	0.0010

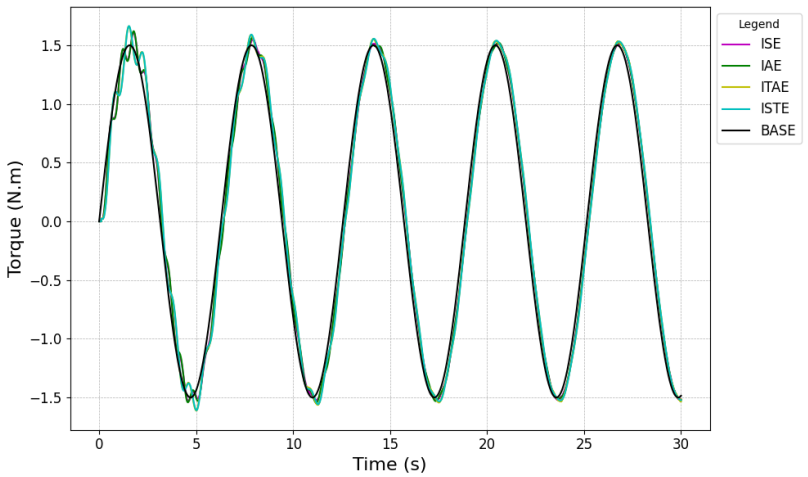


Figure 4. Result in the sinusoidal scenario with different error criteria

Table 4. Performance indices for each optimization criterion (sinusoidal torque input)

Error Criteria	ISE	IAE	ITAE	ISTE	Amplitude ratio	Phase lag (deg)	RMS error
ISE	44.38	322.53	4740.27	12317.59	1.05	355.20	0.12
IAE	47.41	331.46	4855.57	12936.06	1.06	355.20	0.13
ITAE	60.75	371.08	5367.11	15782.69	1.09	354.60	0.14
ISTE	65.29	385.38	5583.20	17077.28	1.09	354.60	0.15

3.2 State Machine vs Single PID Controller

A comparison between a State Machine controller, switching between motor and brake control [8], and a single fixed-gain PID controller optimized for the sinusoidal reference trajectory revealed that the latter outperformed the State Machine. As shown in Fig. 5. The Single PID configuration achieved lower IAE (Tab. 5), showing better adaptability to the sinusoidal input. These results suggest that discrete switching strategies introduce instability and degrade smoothness [8], particularly due to transitions between two actuators with distinct response times.

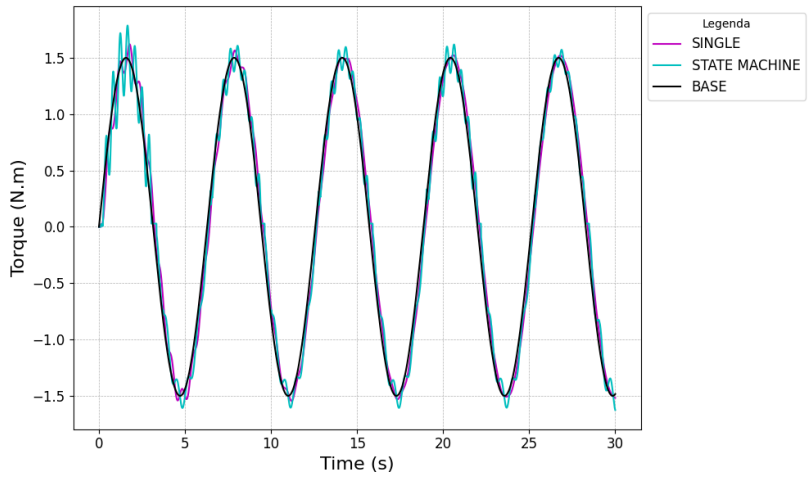


Figure 5. Result comparison between Single PID and State Machine for the hybrid scenario

Table 5. Performance comparison between Single PID and State Machine for the hybrid scenario

Type	ISE	IAE	ITAE	ISTE	Amplitude ratio	Phase lag (deg)	RMS error
SINGLE	47.41	331.46	4855.57	12936.06	1.06	355.19	0.13
ST. MACHINE	58.95	342.80	4721.96	14339.96	1.14	357.00	0.14

3.3 Fuzzy-PID vs Single PID Controller

In the final comparison (Fig. 6), the Fuzzy-PID controller, dynamically adjusting PID coefficients based on the torque regime, outperformed the Single PID configuration in scenarios involving transitions between sinusoidal and resistive step inputs. The fuzzy system demonstrated a reduction in overshoot of nearly 47% and improved performance across all error indices (Tab. 6). These findings confirm the effectiveness of real-time gain adaptation in handling dynamic changes in system behavior [20], [21]. The results corroborate findings from other studies that demonstrate the benefit of Fuzzy-PID tuning in nonlinear and time-varying systems [22].

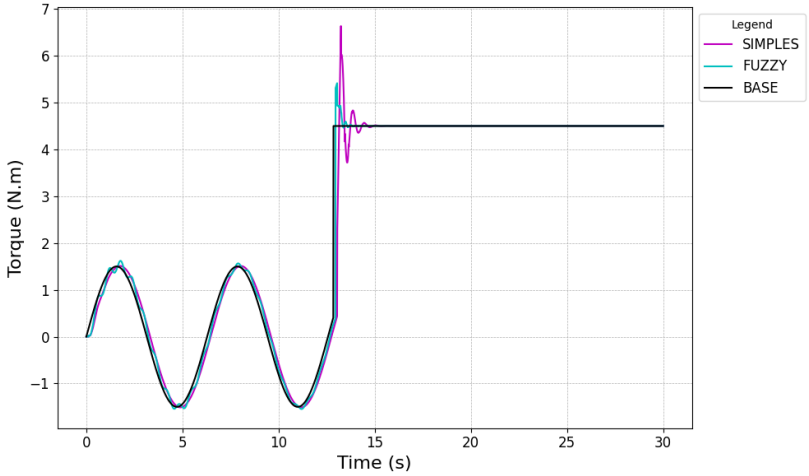


Figure 6. Result comparison between Single PID and Fuzzy-PID switching controller

Table 6. Performance comparison between Single PID and Fuzzy-PID switching controller.

Type	ISE	IAE	ITAE	ISTE	Overshoot	Peak overshoot	Rise time (s)	Settling time (s)	Steady state error
SINGLE	470.00	375.23	3486.26	74127.39	0.32	0.47	12.64	14.25	0.0015
FUZZY	224.71	215.06	1818.92	34793.13	0.17	0.20	12.54	13.49	0.0010

4 Conclusions

This study presented the design and evaluation of a hybrid intelligent control system for a transradial prosthetic wrist, integrating PID control, Fuzzy Logic, and Particle Swarm Optimization (PSO). By modeling the dynamics of the motor-reducer-brake system and employing PSO for PID tuning based on different error indices, particularly IAE, the proposed approach achieved improved tracking performance across various operating scenarios. The results highlighted that IAE-based PID tuning delivered superior balance between error minimization and control smoothness. Furthermore, the comparison between the Single PID and State Machine controllers demonstrated the benefits of continuous control action, minimizing abrupt transitions and enhancing stability. Most notably, the Fuzzy-PID controller significantly improved system performance during regime

transitions, reducing overshoot and improving both transient and steady-state behavior. These findings reinforce the advantages of combining classical control methods with soft computing and bio-inspired optimization strategies for nonlinear, time-varying biomedical systems. Future work will include experimental validation using a physical prosthesis prototype and the extension of the fuzzy rule base to address more complex motion profiles and external disturbances.

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