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## SwarmPID: Enhancing Amphibious Robot Control through Partial Swarm Optimization



**Abstract:** - In the realm of control systems, PID controllers stand out as the go-to choice for their widespread application and user-friendly nature. Achieving optimal performance for complex systems, such as an amphibious robot, hinges greatly on setting the PID controller parameters just right. Traditionally, this has been a painstaking task, often involving manual tuning methods aided by software calculators. However, a promising alternative emerges in the form of particle swarm optimization (PSO). In our study, we employ PSO to efficiently determine the optimal PID controller parameters. This method offers a streamlined approach, leveraging the collective intelligence of particles to navigate the parameter space and converge upon the most effective settings. To evaluate the efficacy of our proposed approach, we meticulously compare its performance against other tuning methods, including pole placement and LQR. Through rigorous testing, we assess the composite control system's behavior under various error conditions and time responses. By embracing PSO for PID parameter tuning, we aim to streamline the optimization process, enhance control system performance, and pave the way for more efficient and reliable operation of complex systems like the amphibious robot.

**Keywords:** Proportional Integral Derivative (PID) Tuning, Partial Swarm Optimization (PSO) method, Linear–quadratic regulator (LQR) method, Pole placement method.

### I. INTRODUCTION

In recent years, research on autonomous amphibious robots has gained significant momentum, resulting in the creation of advanced models with versatile capabilities. These robots, designed to operate on both land and underwater, serve crucial roles in a wide array of high-stakes tasks. Their applications span diverse fields such as pollution detection, exploration, monitoring of amphibious zones, scientific research, and search and rescue operations [1, 2]. The unique ability of these robots to seamlessly transition between different environments underscores their immense value in tackling challenges across various domains. They offer a flexible and adaptable solution to complex problems, making them indispensable assets in addressing a multitude of real-world challenges. Amphibious robots are engineered with a suite of features optimized for effective performance in both water and land environments, each tailored to specific purposes. They come equipped with waterproof seals and casings, providing robust protection for internal components against water damage, thereby ensuring consistent and reliable operation even in wet conditions. Central to their design are buoyancy control systems, which enable the robot to effortlessly float on the water's surface or submerge to varying depths as needed for navigation. These systems play a pivotal role in ensuring the robot's adaptability to aquatic environments. Moreover, specialized propulsion mechanisms are incorporated to facilitate efficient movement across diverse terrains. Whether utilizing wheels, tracks, or propellers, these propulsion systems empower the robot to navigate with agility and precision, seamlessly transitioning between land and water with ease.

In addition to their mechanical attributes, amphibious robots incorporate sensors crucial for detecting and navigating through different environments. These sensors play a pivotal role in identifying obstacles, water currents, and other factors influencing the robot's movement and overall performance. The versatility of amphibious robots extends to their application in disaster scenarios. Capable of locating and rescuing individuals during water-based emergencies such as floods and hurricanes, these robots navigate through flooded regions, reaching otherwise inaccessible areas for safe and effective rescue operations.

Amphibious robots extend their impact beyond crisis response, making substantial contributions to environmental monitoring efforts. Their role is pivotal in identifying pollution and ecological hazards through tasks such as water sample collection, continuous monitoring of water quality, and conducting surveys on wildlife populations and environmental parameters. Moreover, these robots excel in exploring underwater environments, spanning across lakes, rivers, and oceans. Outfitted with a suite of tools including cameras, sensors, and scientific instruments, they provide invaluable insights into marine life and the intricate ecosystems beneath the water's surface, thereby supporting significant scientific research initiatives. Furthermore, their versatility and functionality render them useful in military applications, where their adaptability allows for a range of missions and operations. Overall,

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amphibious robots serve as invaluable assets in diverse contexts, ranging from environmental conservation to military endeavors, owing to their multifaceted capabilities and operational flexibility.

Effectively controlling the actions of such a device poses a significant challenge, prompting researchers to explore a multitude of approaches to tackle this complex task. Some have explored radical design changes, such as adopting novel shapes like spherical [1, 2], fish-shaped [3], or salamander shaped [4] structures. Others have delved into enhancing locomotion performance [5, 6]. A comprehensive investigation into bionic amphibious robots is detailed in [7], while [8] showcases amphibious robots designed for railway maintenance, integrating different sensors and a mobile manipulator.

As a control engineer, the focus lies on designing and analyzing diverse control strategies. This includes established techniques such as linear quadratic regulator (LQR) [9-12], pole placement [13-18], and PID controllers with various tuning methods. In this paper, the design incorporates LQR, pole placement, and Particle Swarm Optimization (PSO) [19-28] to fine-tune the PID controller. Subsequently, thorough time-domain and frequency-domain analyses are conducted. The performance of each controller is assessed using metrics like Integral of Squared Time Error (ISTE), Integral of Time-weighted Absolute Error (ITAE), Integral of Absolute Error (IAE), and Integral of Error (IE). This comprehensive evaluation aims to provide insights into the efficacy of the different control strategies employed.

The paper's structure is well-organized, maintaining a logical flow throughout its sections. In Section I, the introduction provides a concise overview of amphibious robot speed control, emphasizing its importance and outlining the paper's objectives and scope. Section II delves into the proposed methodology for speed control, detailing the advanced approach and justifying its selection over alternatives. Section III focuses on Particle Swarm Optimization (PSO) PID as a crucial element, explaining its concepts and role within the method. Section IV presents simulation results and comparative analysis, comparing outcomes with existing methodologies and exploring strengths and limitations. Finally, Section V concludes by summarizing key findings, highlighting the proposed method's advantages, and suggesting future research directions.

## II. BLOCK DIGRAM OF PROPOSED METHOD

Figure 1 outlines the steps of the proposed method, focusing on tuning the PID controller using PSO optimization. Reference [29] offers a comprehensive control system for an amphibious spherical bot, crucial for anticipating robotic motion in response to disturbances. PSO optimization demonstrates superior performance, especially in predicting low-impact disturbances, making it ideal for optimizing input parameters in the proposed method [29,30].

Input parameters are provided for simulations, where performance index and time responses serve as validation metrics. Additionally, disturbances are deliberately introduced during testing to assess the robustness of the proposed method.

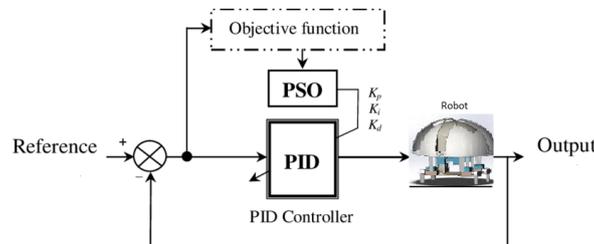


Fig. 1 Block Diagram of Amphibious Robot movement control using PSO-PID optimization

### A. Explanation of Movement Control System:

Amphibious spherical robots have variable control parameters [31]. The water jet is driven by a servo motor to swing back and forth. Changing the PWM signal causes the spherical robot to walk at different speeds [31]. Control of amphibious spherical robot. The robot CPU is an AVR micro unit. 4 Turn on the servo motor to generate a PWM signal to start the water motor. PWM signals are used to adjust the movement of the robot in water [32, 33]. Each unit includes a motor, servo motor and stainless-steel water jet. Four amphibious airship robots spread their spheres around the room. PWM signal is used to control the movement of the motor. Servo motor can rotate 180 degrees. Another motor connected to the sprinkler is controlled to move at the same time [33]. Each unit can use a servo motor to achieve two degrees of freedom of movement. Thruster rotation is controlled by eight servo motors. When the amphibious spherical robot walks on the ground, each drive module has two degrees of freedom and acts as two legs. Quadruped robots have four legs to move around. Adjusting the PWM signal can make the robot walk and rotate on the ground.

## III. DETAILS OF DIFFERENT STRATEGIES USED TO CONTROL THE AMPHIBIOUS ROBOT:

There are different methods of tuning the PID controller. In this paper Pole Placement method and Linear Quadratic Regulator (LQR) are used for comparison

### A. Linear Quadratic Regulator (LQR):

LQR is a control strategy which involves minimizing cost function that combines deviations from desired states and control effort. LQR is effective for linear time-invariant systems, providing optimal control gains to achieve stability and performance. It's widely used in engineering for applications like robotics and aerospace. In the context of an amphibious robot, LQR (Linear Quadratic Regulator) can be significant for several reasons:

- **Optimal Control:** LQR is designed to find control inputs that optimize a performance criterion. In the case of an amphibious robot, this could mean efficiently transitioning between water and land, optimizing energy consumption, or achieving desired navigation goals.
- **Adaptability to Dynamic Environments:** Amphibious environments often pose dynamic challenges. LQR allows the robot to adapt its control strategy in real-time based on the system's dynamics, enhancing its ability to handle changing conditions.
- **Stability:** LQR provides control gains that ensure stability for the robot. In an amphibious setting where the robot encounters varying
- **Energy Efficiency:** Controlling the poles allows for the optimization of energy consumption during transitions and while operating in various environments. This is essential for amphibious robots, where energy efficiency contributes to prolonged operational time.
- **Precision in Navigation:** Amphibious robots often require precise navigation for tasks such as underwater inspections or land-based exploration. Pole placement enables the design of control strategies that provide the necessary precision in navigation and positioning.
- **Response to Environmental Uncertainties:** Amphibious environments can be unpredictable with factors like currents, waves, and varied terrains. Pole placement allows for designing control systems that respond effectively to these uncertainties, enhancing the robot's robustness.
- **Seamless Transitions:** Achieving seamless transitions between aquatic and terrestrial modes is a critical aspect of amphibious robot control. Pole placement plays a key role in designing controllers that facilitate smooth transitions, minimizing disruptions in the robot's operation.

In LQR, for the robot, consider a linear model with state space equation (1) given by,

$$\dot{X} = AX + Bu(X(t_0) = X_0) \quad (1)$$

$$Y = CX + Du(t)$$

Where, X, u(t), optimal control signal, state model matrix are represented by A, B and C. X<sub>0</sub> defines a set initial value of the state vectors of a robot model [40]. The feedback gain matrix is calculated through K using the Algebraic Riccati equation (ARE) as given in equation (2).

$$K = R^{-1}B^T P [p_{13} \ p_{23} \ p_{33}] \quad (2).$$

### B. Pole Placement Method

All of the state variables in the Pole Placement or Pole assignment technique should be measurable and accessible to the feedback mechanism with precise sensor values. Poles of the closed-loop system with plant can be positioned anywhere via a state feedback mechanism for a fully state controllable system, which is obtained through an appropriate state feedback gain matrix K [34]. For a specific type of linear control system, the pole-placement technique also referred to as eigen structure assignment— is utilized. The controller's goal is to simultaneously assign a linear system's eigenvalues and eigen-vectors by modifying the feedback gain (using output feedback or state feedback). The closed loop system's stability and, to some extent, its bandwidth are determined by the system's eigen values, and the degree to which each eigen value affects each state variable's response is determined by the eigen vectors. [34]. For Pole place mechanism the feedback control law is given in equation (3) as,

$$\dot{x}(t) = (AB - K)x(t) \quad (3)$$

Pole placement in the context of amphibious robot control holds several significant implications:

- **Adaptive Control for Transitioning:** Amphibious robots often need to transition between different adaptive control strategies, enabling the robot to smoothly transition and stabilize in each environment by strategically placing poles.
- **Stability in Diverse Environments:** Amphibious environments are dynamic and diverse. Pole placement is crucial for ensuring stability in the face of changing conditions, helping the robot maintain control and balance as it moves between water and land.
- **Optimizing Locomotion:** Amphibious robots use different propulsion mechanisms in water and on land. Pole placement facilitates the optimization of locomotion by influencing the closed-loop dynamics, helping the robot achieve efficient and effective movement in both environments.

In summary, pole placement is significant in amphibious robot control as it enables the design of adaptive, stable, and efficient control strategies.

C. Particle Swarm Optimization (PSO) for PID optimization:

PID controllers are extensively utilized across industries such as chemical, gas, and oil due to their proven reliability and robustness in overseeing various processes. Their attractiveness to businesses lies in their affordability, ease of maintenance, and straightforward control structure. Consisting of proportional, integral, and derivative components, a PID controller operates by computing the current error value, evaluating the cumulative history of recent errors, and adjusting the response to effectively correct the error. The controlled system's behavior is shaped by the combined effect of these three actions, resulting in precise and efficient control over the process. [35, 36].

In real-world scenarios, complexities like parameter fluctuations, time delays, and other dynamics can complicate the process of adjusting control parameters. Tuning PID controllers becomes crucial to ensure optimal closed-loop performance across various operating conditions. Improper tuning of PID controllers can lead to issues such as delayed cycling and sluggish recovery, potentially resulting in system failure. This study aims to pinpoint vulnerabilities in PID controllers, shedding light on areas that require attention and refinement for enhanced performance and stability. [36].

Several techniques have been put forward for identifying optimal PID parameters, with Ziegler-Nichols and Cohen-Coon being prominent methods. Despite its widespread recognition, the Ziegler-Nichols (ZN) approach sometimes falls short in delivering satisfactory regulation, occasionally leading to suboptimal control outcomes [37]. In response to this limitation, an enhanced Particle Swarm Optimization (PSO) algorithm has been introduced to fine-tune PID parameters for a particular robot. This improved method offers a promising solution for achieving more precise and effective control, addressing the shortcomings of traditional approaches like Ziegler-Nichols [37].

In the context of brushless DC (BLDC) motor speed control, an effective control system based on PSO is implemented, as presented in [36]. To tackle challenges associated with PID tuning, [38,39] introduces new parameter selection guidelines along with a modified version of PSO [40], offering potential improvements in controlling systems with enhanced precision.



Fig. 2 Flow chart of step for PSO-PID optimization

The Particle Swarm Optimization (PSO) algorithm is widely employed in scientific research and exhibits excellent adaptability in optimizing control parameters [41]. PSO operates as a multi-agent parallel search method, where particles explore a multi-dimensional search space. Each particle possesses a specific position and velocity at any given moment, representing a potential solution to the search problem through position vectors as shown in flow chart of figure (2). Random velocities  $V_i$  and positions  $X_i$  initialize a population of particles at the outset, collectively known as a “swarm (S).”

Within the swarm, a unique neighborhood relation (N) is established, determining the relationship between two particles  $P_i$  and  $P_j$ . The function of this relation involves adjusting settings to minimize the objective function, aiming to discover the optimal solution. The evaluation of associated characteristics, including rise time, maximum overshoot, settling time, gain margin, and phase margin, is conducted. These parameters serve as metrics for comparing various optimization techniques, contributing to the overarching goal. Utilizing a set of performance indicators, the efficacy of tuning techniques can be assessed, making them valuable tools in the design process.

$$V_i^{t+1} = wv_{i,m}^t + C_1(P_{best,i,m}^t - x_{i,m}^t) + C_2(G_{best} - x_{i,m}^t) \tag{4}$$

$v_i, m$  Velocity of particle  $i$  at iteration  $t$ , dimension  $m$ ,  $x_{i,m}^t$  Current position of particle  $i$  at iterations,  $P_{best, i, m}$  Best previous position of the  $i^{th}$  particle,  $G_{best}$  Best particle among all the particles. Velocity is updated given in equation 4. Position is updated with equation 5.

$$x_i^{t+1} = x_{i,m}^t + V_{i,m}^{t+1} \tag{5}$$

Particle Swarm Optimization (PSO) can be employed as a tuning technique for PID (Proportional-Integral-Derivative) controllers to automatically find optimal or near optimal controller parameters. Here’s how the process typically works:

1. **Parameter Representation:** In the context of tuning a PID controller using PSO, each particle in the swarm represents a set of PID parameters (proportional gain, integral gain, and derivative gain).
2. **Objective Function:** The fitness or objective function evaluates the performance of the PID controller with the given parameters. Common performance metrics include settling time, overshoot, or integral of squared error.
3. **Initialization:** Initialize a population of particles with random PID parameter values within specified
4. **Evaluation:** Evaluate the fitness of each particle by simulating the closed-loop system’s response to a given set of disturbances or reference signals.
5. **Update Particle Velocities and Positions:** Update each particle’s velocity and position based on its personal best-known position and the global best-known position. This update is influenced by inertia, cognitive, and social components, similar to standard PSO.
6. **Iterative Optimization:** Repeat steps 4 and 5 for a certain number of iterations or until convergence criteria are met.
7. **Optimal PID Parameters:** The final positions of the particles represent sets of PID parameters. The best position found by any particle corresponds to the optimal or near-optimal PID parameters.
8. **Apply Tuned PID Controller:** Implement the PID controller with the tuned parameters in the actual system.

#### IV. RESULTS AND DISCUSSION

The primary goal of the proposed approach is to control the movement of a robot capable of navigating both on land and in the sea. The design of the robot model incorporates hydrodynamic forces and moments, which are regarded as damping factors [9]. These factors are essential for accurately simulating the robot's behavior in aquatic environments. Utilizing the transfer function specified in equation 6, specific values for the robot parameters are employed. These parameter values play a critical role in shaping the characteristics and performance of the robot within the control system.

$$G(s) = \frac{1}{3.987s^2 + 0.95s + 0.2097} \tag{6}$$

PSO method is compared with open loop system, unity feedback system [42], PID controller [43], pole placement method [40], and LQR optimization [44]. Analysis of time domain parameters is used to compare it. The suggested method’s step response is displayed alongside other current methods in Figure 3. PID overshoot and higher steady state error are depicted in Figure 3; to decrease these, PID is tuned using PSO optimizations. The suggested method outperforms the alternatives. Error depicts the difference between the set point and process variable. It uses a PID controller to calculate continuously. Error is reduced by modifying a control variable, like a robot’s position or motor speed, among others.

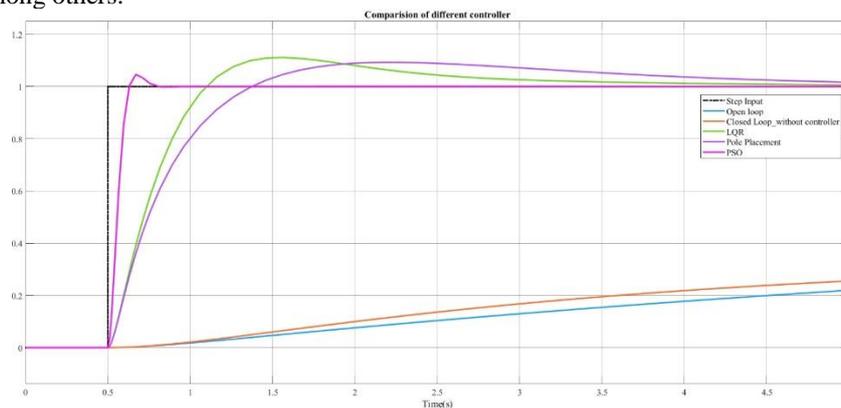


Fig. 3 Comparative results using step response: Proposed PSO method with pole placement, LQR optimization

The robustness of a controller is assessed by introducing disturbances, aiming to evaluate its ability to handle disruptions and minimize errors. The proposed method demonstrates superior management of disturbances compared to alternative approaches, as illustrated in Figure 4.

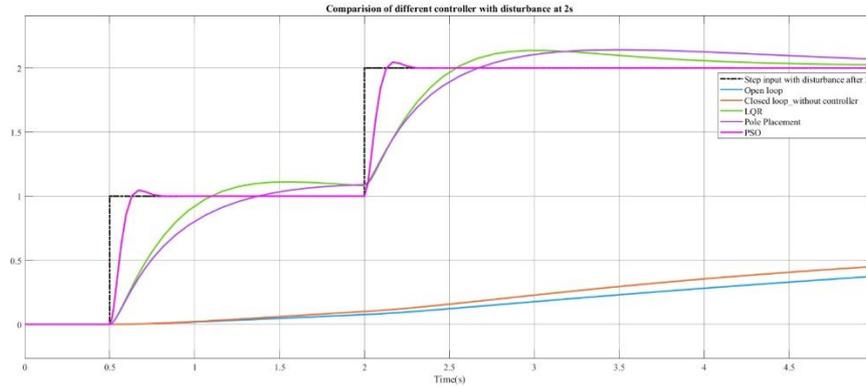


Fig. 4 Comparative results using step response adding disturbance: Proposed PSO method with pole placement, LQR optimization

The Nyquist plot stability analysis method offers a straightforward way to assess the stability of systems, particularly those with delays and non-rational transfer functions. This graphical representation indicates stability by the number of encirclements around a specific point, typically ranging from negative 1 to zero. Figure 5 displays the Nyquist plot for each method system, with the outcome revealing the stability of the PSO method. The Nyquist plot holds significant importance for several reasons:

- Frequency Response Visualization: It provides a visual depiction of how a system reacts to different frequencies, showcasing the gain and phase shift across the frequency spectrum.
- Stability Analysis: Engineers can determine the stability of a system by examining the Nyquist plot. A stable closed-loop system should not encircle the critical point  $(-1, j0)$  in the complex plane.
- Margin of Stability: The distance between the Nyquist plot and the critical point  $(-1, j0)$  indicates the system's stability margin. A larger margin signifies greater stability and robustness.

In essence, the Nyquist plot serves as a powerful tool in control system analysis, offering clarity and intuition regarding a system's frequency response, aiding in stability analysis, controller design, and comprehension of complex system dynamics.

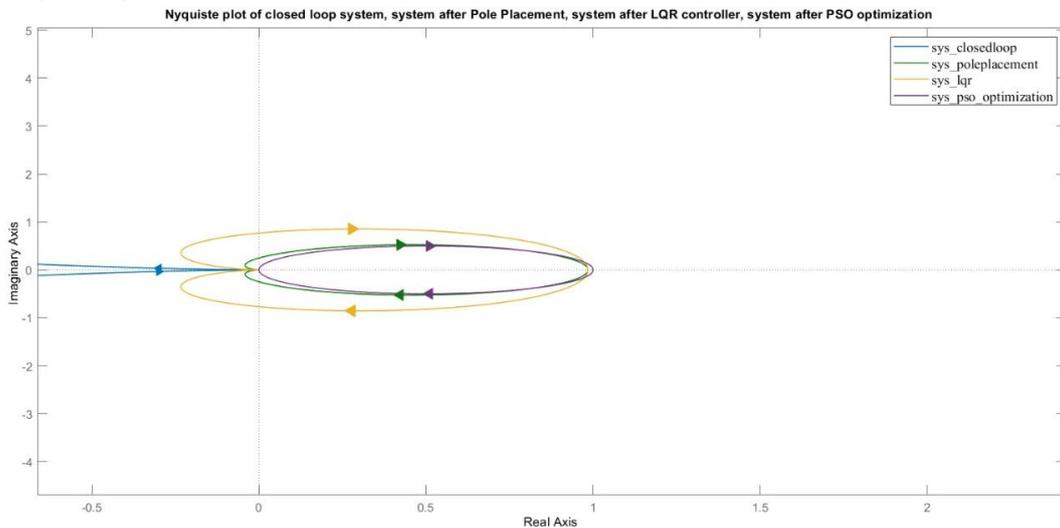


Fig. 5 Nyquist plot for all method a proposed PSO method for Stability analysis

Table I presents a comparative analysis of outcomes, showcasing the performance of different approaches. The proposed method demonstrates superior performance compared to other current approaches, with better outcomes highlighted in bold. The quantitative values of the time response, including settling time and overshoot, are provided in the table. Notably, the proposed PSO method exhibits improved settling time and absence of overshoot, distinguishing it as a favorable approach.

Table I: Quantitative analysis of proposed PSO method using time response (better values are highlighted)

Name of method	Rise time	Peak	Overshoot	Settling time
Unity feedback	5.33	7.11	49.96	74.07

Pole placement	16.13	<b>0.98</b>	<b>0.0</b>	29.17
LQR optimization	<b>3.87</b>	1.05	7.27	11.89
PSO method	7.96	1.00	<b>0.0</b>	<b>1.41</b>

The terms ISTE (Integral of Squared Time Error), ITAE (Integral of Time-weighted Absolute Error), IAE (Integral of Absolute Error), and IE (Integral of Error) are performance criteria or indices utilized in control engineering to assess the performance of a control system. Each criterion represents a distinct approach to quantifying the integral of the error signal over time.

Errors such as ITAE, IAE, ISE, and ITSE are commonly used in control system analysis. The ITSE (Integral of Time multiplied by the Squared Error) equation serves as a performance criterion, evaluating the control system's capability to minimize both the error magnitude and the duration over which the error persists. Mathematically, it is expressed in equation (7) as:

$$ITSE = \int_0^{\infty} te(t)^2 dt \tag{7}$$

where t is the time, y is the controller's output, and x is the set point. Time multiplied integral the absolute error multiplied by the time over time is known as the Absolute Error (ITAE) [9] It is given as equation (8),

$$ITAE = \int_0^{\infty} t|e(t)|dt \tag{8}$$

ITAE assigns different weights to errors at different times. It emphasizes minimizing the integral of the absolute error over time, giving more importance to errors that occur earlier in the system's response. This can be useful when rapid settling is a priority.

The Integral of Absolute Error (IAE) integrates the absolute error over time. It is given as equation (9),

$$IAE = \int_0^{\infty} |e(t)|dt \tag{9}$$

IAE focuses on minimizing the total absolute error over time. It treats positive and negative errors equally, providing a balanced assessment of the system's performance. IAE is commonly used when the magnitude of the error is critical, regardless of its sign.

The system performance indicator for a fixed interval of time, the Integral of Squared Error (ISE), is provided in equation (10)

$$ISE = \int_0^{\infty} e(t)^2 dt \tag{10}$$

Low values are optimal for optimal performance. Table II compares the suggested method's results with those of the current methods by utilizing error values. In terms of disturbance conditions, the suggested method outperforms other current methods.

Table II shows comparative result of the suggested method without disturbance whereas Table III shows comparative result of the suggested method with disturbance. In terms of disturbance conditions, the suggested method outperforms other current methods.

Table. II: Quantitative analysis of proposed PSO method using Error (better values are highlighted)

Name of method	IE	IAE	ISE	ITSE	ITAE
Open loop	4.5	4.5	4.5	12.38	12.28
Unity feedback	3.86	3.86	3.35	10.17	10.17
Pole placement	0.09	0.50	0.19	-0.38	0.79
LQR optimization	0.08	0.39	0.16	-0.18	0.79
PSO proposed method	<b>0.05</b>	<b>0.06</b>	<b>0.04</b>	<b>0.02</b>	<b>0.03</b>

Tab. III Quantitative analysis of proposed PSO method for system using disturbance using errors (better values are highlighted)

Name of method	IE	IAE	ISE	ITSE	ITAE
Open loop	7.5	7.5	13.5	22.88	22.88
Unity feedback	6.57	6.57	10.23	19.50	19.50
Pole placement	0.24	0.81	0.33	0.30	1.74
LQR optimization	0.19	0.71	0.30	0.14	1.37
PSO proposed method	<b>0.10</b>	<b>0.12</b>	<b>0.08</b>	<b>0.13</b>	<b>0.17</b>

### V. CONCLUSION

This paper introduces a novel control design aimed at regulating the movement of amphibious robots. In comparison to conventional PID control methods, the proposed approach, leveraging PSO optimization for PID tuning, exhibits superior performance. Specifically, the proposed method entails employing a PID controller

enhanced with PSO optimization for dynamic control of the robot's movement. Compared to traditional PID control, the proposed method demonstrates a shorter resolution time for overshoot, indicating faster response and improved control precision. By utilizing PSO optimization to fine-tune the parameters of the PID controller, the proposed method effectively reduces error and enhances overall performance, thereby minimizing problem-solving times. Furthermore, the proposed method is evaluated against a frequency analysis utilizing the Nyquist principle, revealing its superiority over alternative approaches. Through a comprehensive comparison of results and an in-depth analysis of its efficacy, the proposed method emerges as a more effective solution for controlling amphibious robot movement.

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