
Adaptive Objective Function Design for Genetic Algorithm-Based PID Control of Brushed DC Motors

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KEYWORDS

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ABSTRACT

This study presents an advanced methodology for improving the performance of brushed DC motors through an adaptive objective function design for Genetic Algorithm (GA)-based PID controllers. Conventional GA-PID tuning methods often rely on static objective functions, which limit their ability to simultaneously optimize multiple performance criteria, including rise time, overshoot, settling time, steady-state error, and energy consumption. To address these limitations, the proposed framework introduces a dynamic weighting mechanism within the GA fitness function, allowing the controller to prioritize different performance objectives adaptively during various phases of motor operation. The research employs both simulation and real-time hardware validation using a 24V brushed DC motor controlled via FPGA, ensuring that theoretical results translate effectively into practical applications. Simulation results demonstrate that the adaptive GA-PID significantly outperforms conventional GA-PID controllers, reducing rise time by approximately 43%, overshoot by nearly 68%, and settling time by 44%, while maintaining steady-state errors below 0.3%. Energy efficiency also improved by 6–7% due to optimized torque allocation. Hardware experiments corroborate these findings, showing robust speed regulation under varying load torques from 0.05 to 0.6 Nm and consistent real-time adaptation of PID parameters without destabilizing the system. Comparative analysis with literature reveals that the adaptive objective function approach effectively integrates multi-objective optimization in a computationally efficient manner, avoiding the complexities of fuzzy logic or multi-heuristic GA methods while maintaining high precision and robustness. The framework's practical implications extend to industrial automation, robotics, and precision electromechanical actuation, where both performance and energy efficiency are critical. Limitations related to computational overhead and adaptation rate tuning are addressed, and strategies for mitigating these challenges in resource-constrained systems are discussed. Overall, this research provides a novel, systematic, and experimentally validated approach to GA-based PID optimization, establishing a foundation for future work in adaptive control, predictive optimization, and multi-motor coordinated systems. The methodology demonstrates that dynamic fitness adaptation not only improves transient and steady-state performance but also enables energy-conscious, scalable, and robust control of electromechanical systems, thereby contributing to both theoretical advancements and practical engineering solutions.

INTRODUCTION

The brushed DC (Direct Current) motor remains a cornerstone in industrial automation, robotics, and precision electromechanical applications due to its simplicity, high torque-to-weight ratio, and ease of speed control. Despite these advantages, precise control of brushed DC motors presents a persistent challenge, primarily because of system nonlinearities, varying load conditions, and parameter uncertainties. Traditional PID (Proportional–Integral–Derivative) controllers are widely employed for DC motor regulation due to their simplicity, reliability, and ease of implementation. However, conventional PID control often struggles to simultaneously achieve fast transient response, minimal overshoot, and optimal energy efficiency, particularly under dynamic operating conditions.

To address these limitations, optimization algorithms such as Genetic Algorithms (GA) have been extensively applied to PID controller tuning. GA provides a stochastic, population-based search mechanism capable of navigating complex, multidimensional parameter spaces, making it particularly suitable for systems with nonlinearities and uncertain dynamics (A. Mirzal et al., 2012; T. O. Mahony et al., 2000). Prior studies have demonstrated that GA-based PID tuning can significantly enhance motor performance, including overshoot reduction, improved rise time, and minimization of steady-state errors (A. A. Aly, 2011; M. A. Ibrahim et al., 2019). Nevertheless, these approaches typically employ static objective functions, in which multiple performance metrics are combined using fixed weights. While effective under limited conditions, static objective functions often constrain the GA's search capability, leading to suboptimal trade-offs between competing performance indices such as transient response, steady-state accuracy, and energy consumption.

Recent research has explored adaptive and multi-objective approaches to PID optimization to

overcome these limitations. Techniques integrating fuzzy logic, particle swarm optimization, or multi-objective GA frameworks have been proposed to enhance flexibility and dynamic performance (N. N. Baharudin & S. M. Ayob, 2018; A. Sungthong & W. Assawinchaichote, 2016). While these methods provide some improvement, they often require complex rule-setting, high computational resources, or offline tuning, limiting their practicality for real-time applications. Furthermore, experimental validation in hardware systems is frequently limited or absent, leaving uncertainty regarding their performance in dynamic load environments typical of industrial operations.

In this context, the current study introduces a novel adaptive objective function design for GA-based PID control, which dynamically adjusts the weighting of multiple performance criteria throughout the optimization process. By adapting the emphasis on transient response, overshoot, steady-state error, and energy efficiency based on real-time system behavior, the GA search is guided more effectively toward globally optimal PID parameters. This adaptive approach ensures that the controller not only maintains precise speed regulation under varying load conditions but also optimizes energy utilization, a critical consideration in contemporary electromechanical systems (A. A. M. Zahir et al., 2018; C. F. Hsu & B. K. Lee, 2011).

The objectives of this research are fourfold:

1. To design an adaptive objective function framework capable of dynamically balancing multiple PID performance metrics.
2. To integrate this framework with GA-based PID optimization for brushed DC motors.
3. To validate the approach via simulation and FPGA-based hardware implementation, ensuring practical feasibility.

4. To critically evaluate the improvements over conventional static-objective GA-PID controllers in terms of transient response, overshoot, settling time, steady-state error, and energy efficiency.

The scope of the research encompasses both theoretical modeling and experimental validation, focusing on single brushed DC motor control under varying load conditions. While the study emphasizes brushed DC systems, the principles of adaptive objective function design can be extended to other electromechanical and robotic systems requiring multi-objective optimization.

The significance of this work lies in its combination of theoretical innovation, computational efficiency, and practical validation. By introducing dynamic weighting in GA-based PID tuning, this study addresses a critical research gap in adaptive multi-objective optimization and provides a robust, energy-efficient control strategy suitable for real-world industrial and robotic applications. The methodology is designed to bridge the divide between simulation-based controller design and practical hardware implementation, offering a scalable and adaptable framework for future electromechanical control systems.

LITERATURE REVIEW

Significant research has addressed GA-based PID optimization in motor control. Early studies applied fixed-objective GA tuning, demonstrating improvements in overshoot, settling time, and steady-state error (T. O. Mahony et al., 2000; A. Mirzal et al., 2012). However, these approaches were limited by static fitness evaluations that could not adapt to load variations or multi-objective performance criteria (H. E. Ibrahim et al., 2014).

C. F. Hsu and B. K. Lee (2011) implemented FPGA-based adaptive PID control, highlighting hardware-level adaptability but lacking dynamic GA objective integration. Similarly, M. B. N. Shah et al. (2019) focused on PID applications in temperature control, emphasizing error minimization yet relying on fixed indices.

Adaptive PID optimization strategies incorporating fuzzy logic or multi-objective formulations have been explored (A. Prayitno et al., 2018; N. N. Baharudin & S. M. Ayob, 2018). These studies demonstrate improved convergence and robustness, but they do not fully exploit the GA's ability to dynamically modulate objective functions based on system feedback (A. A. Aly, 2011).

Further, recent works in energy-based and exergy optimization for electromechanical systems (Nasruddin et al., 2018) underscore the necessity of integrating multi-dimensional performance metrics into fitness evaluation. By reviewing these contributions, the present study identifies a gap in real-time adaptive objective function design within GA-PID frameworks, particularly for hardware-intensive brushed DC motor systems (M. M. A. Alqadasi et al., 2019; A. A. M. Zahir et al., 2018).

METHODOLOGY

3.1 System Model of Brushed DC Motor

A standard brushed DC motor is modeled by the differential equations relating armature voltage, current, torque, and speed:

$$\begin{aligned} V_a(t) &= L \frac{di_a(t)}{dt} + R i_a(t) + K_e \omega(t) \\ T_m(t) &= K_t i_a(t) \end{aligned}$$

Where V_a is armature voltage, L is inductance, R is resistance, i_a is current, K_e is back EMF constant, ω is angular speed, and T_m is torque. This mathematical representation provides the basis for PID control design (W. Yan et al., 2012).

3.2 PID Control Framework

The PID controller output $u(t)$ is given by:

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt}$$

Where K_p, K_i, K_d are proportional, integral, and derivative gains, and $e(t)$ is the error between reference and actual speed. The gains are optimized using GA with adaptive objective functions, replacing static fitness evaluation with dynamic criteria that account for overshoot, settling time, steady-state error, and energy consumption simultaneously (A. A. Aly, 2011).

3.3 Adaptive Objective Function Design

The proposed fitness function FFF is defined as:

$$F = w_1 IAE(t) + w_2 \text{Overshoot} + w_3 \text{SettlingTime} + w_4 \text{EnergyUsage}$$

Weights w_1, w_2, w_3, w_4 are dynamically adjusted based on real-time system performance metrics, allowing the GA to prioritize different control objectives as operating conditions change. This strategy improves convergence towards globally optimal PID parameters while maintaining robustness against load disturbances (A. A. M. Zahir et al., 2018; G. A. Salman et al., 2019).

3.4 Genetic Algorithm Implementation

The GA optimization procedure includes:

1. Population Initialization: Random generation of PID gain sets.
2. Fitness Evaluation: Using the adaptive function FFF.
3. Selection: Roulette wheel or tournament-based selection of parent chromosomes.
4. Crossover and Mutation: Generation of offspring with diversity preservation.
5. Termination: Convergence when the fitness improvement falls below a predefined threshold.

The integration of adaptive objective functions enables the GA to dynamically adjust selection pressure, ensuring robust PID performance across varying motor loads and speed trajectories (M. A. Ibrahim et al., 2019; X. Huang et al., 2019).

3.5 Simulation and Experimental Setup

Simulations were conducted using MATLAB/Simulink, modeling a 24V brushed DC motor with varying load torques. Hardware experiments employed an actual DC motor setup interfaced with an FPGA-based controller for real-time gain updates (C. F. Hsu & B. K. Lee, 2011; A. Prayitno et al., 2018). Performance metrics included rise time, overshoot, settling time, and steady-state error.

RESULTS

The adaptive objective function GA-PID controller was evaluated through both simulation and hardware experiments. The performance metrics analyzed included rise time, overshoot, settling time, steady-state error, and energy consumption. For comparative purposes, conventional GA-PID controllers using fixed objective functions were also tested.

4.1 Simulation Results

In MATLAB/Simulink simulations, the proposed adaptive GA-PID demonstrated superior transient response. Under a step input of 1000 rpm reference speed with a variable load torque of 0.1–0.5 Nm, the controller achieved:

- Rise Time: 0.12 s, compared to 0.21 s for conventional GA-PID.
- Overshoot: 2.5%, versus 7.8% for fixed-objective GA.
- Settling Time: 0.35 s, reduced from 0.63 s in the conventional approach.
- Steady-State Error: <0.3%, indicating near-perfect tracking.

Energy consumption analysis showed a 6.7% reduction due to more efficient torque allocation over varying loads. The adaptive weighting in the objective function allowed the GA to emphasize overshoot minimization during initial transients and energy optimization during steady-state operation (A. A. Aly, 2011; M. A. Ibrahim et al., 2019).

4.2 Hardware Experiment Results

Experimental validation employed a 24V brushed DC motor controlled via FPGA. Real-time PID parameter updates were executed based on the adaptive objective function outputs. Key observations included:

- The controller maintained robust speed regulation across load changes from 0.05 to 0.6 Nm.
- Transient overshoot remained below 3%, with settling times consistently under 0.4 s.
- The adaptive GA-PID outperformed the fixed-objective GA-PID in all tested scenarios, confirming simulation results.
- Energy efficiency improved, with average armature current reductions of approximately 5.9%.

These results confirm the practical applicability of adaptive objective functions in real hardware systems, bridging simulation-based design and physical implementation (A. A. M. Zahir et al., 2018; C. F. Hsu & B. K. Lee, 2011).

4.3 Performance Comparison

Metric	Conventional GA-PID	Adaptive GA-PID	Improvement
Rise Time (s)	0.21	0.12	42.8%
Overshoot (%)	7.8	2.5	67.9%
Settling Time (s)	0.63	0.35	44.4%
Steady-State Error (%)	1.2	0.3	75.0%
Energy Consumption	Baseline	-6.7%	6.7%

The adaptive framework clearly outperforms conventional GA-PID controllers in all critical metrics, demonstrating both theoretical and practical benefits.

DISCUSSION

The results highlight several important insights regarding the design of adaptive objective functions for GA-based PID control.

5.1 Theoretical Implications

The study demonstrates that static fitness functions constrain the GA’s ability to explore optimal PID parameter spaces fully. By dynamically adjusting weights in response to system performance, the GA maintains multi-objective optimization throughout transient and steady-state operation (A. A. Aly, 2011). This approach effectively integrates error minimization, overshoot suppression, and energy efficiency, providing a generalized optimization framework applicable to other electromechanical systems (M. M. A. Alqadasi et al., 2019; X. Huang et al., 2019).

5.2 Practical Implications

Hardware experiments confirm the method’s robustness in real-world conditions. The adaptive GA-PID maintained stability under variable loads and non-ideal electrical conditions, outperforming fixed-objective GA-PID controllers. These findings suggest applicability in industrial automation, robotics, and precision actuation where both high performance and energy efficiency are critical (G. A. Salman et al., 2019; A. Prayitno et al., 2018).

5.3 Trade-offs and Limitations

While the adaptive framework improves performance, it introduces additional computational complexity due to real-time weight adjustments. FPGA implementation mitigates this, but resource-constrained systems may face limitations. Furthermore, tuning the adaptation rate of the weights remains a critical design decision, as overly

aggressive adjustments can destabilize the GA search process (H. E. Ibrahim et al., 2014).

5.4 Comparison with Literature

The findings align with prior studies emphasizing GA-PID optimization (A. Mirzal et al., 2012; T. O. Mahony et al., 2000), while extending them by incorporating adaptive objective functions. Compared to fuzzy logic or multi-objective GA-PID approaches (N. N. Baharudin & S. M. Ayob, 2018; A. Sungthong & W. Assawinchaichote, 2016), this method offers a simpler yet more responsive adaptation mechanism. The study validates that the combination of GA with adaptive objectives enhances controller efficiency without requiring complex heuristic rules.

CONCLUSION

This research presents an adaptive objective function approach for GA-based PID tuning in brushed DC motors. Key conclusions include:

1. Enhanced Control Performance: The adaptive GA-PID significantly improves rise time, overshoot, settling time, and steady-state error compared to conventional GA-PID controllers.
2. Multi-Objective Optimization: Dynamic weighting allows simultaneous consideration of error metrics and energy efficiency, providing a comprehensive performance improvement.
3. Hardware Feasibility: FPGA-based real-time implementation confirms practical applicability in electromechanical systems.
4. Research Contribution: The study fills a gap in adaptive objective function integration for GA-PID controllers, demonstrating theoretical and experimental validity.

Future Scope:

- Extension to nonlinear and high-inertia systems.
- Integration with machine learning predictors for

anticipatory control adjustments.

- Application in multi-motor coordination scenarios in robotics and industrial automation.

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