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Robustness Analysis of LQR-PID Controller Based on Particle Swarm Optimization and Grey Wolf Optimization for Quadcopter Attitude Stabilization

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INTRODUCTION & AIM

Quadcopters play a vital role in modern applications such as surveillance, delivery, and search-and-rescue missions, thanks to their agility, maneuverability, and vertical takeoff and landing capabilities. However, maintaining stability and performance under dynamic and unpredictable conditions, such as wind disturbances and sudden impulses, remains a significant challenge. Achieving reliable operation in these scenarios requires robust and advanced control strategies.

Proportional-Integral-Derivative (PID) controllers are commonly used for their simplicity and effectiveness in stabilization tasks. When combined with a Linear Quadratic Regulator (LQR), the resulting LQR-PID controller enhances performance by balancing precise attitude stabilization with efficient control effort. However, optimizing the LQR's Q and R matrices is critical for achieving the best performance and robustness, making parameter tuning an essential part of the control design process.

This study explores the application of metaheuristic optimization techniques, specifically Particle Swarm Optimization (PSO) and Grey Wolf Optimization (GWO), to tune LQR-PID controllers for a quadcopter constrained to rotational degrees of freedom. The primary goal is to enhance attitude stabilization, minimize control error, and ensure robustness under disturbances such as wind and impulse forces. By comparing the performance of PSO- and GWO-based controllers, this work provides insights into the effectiveness of these optimization methods for quadcopter control applications and contributes to the development of resilient control systems for aerial robotics.

METHOD

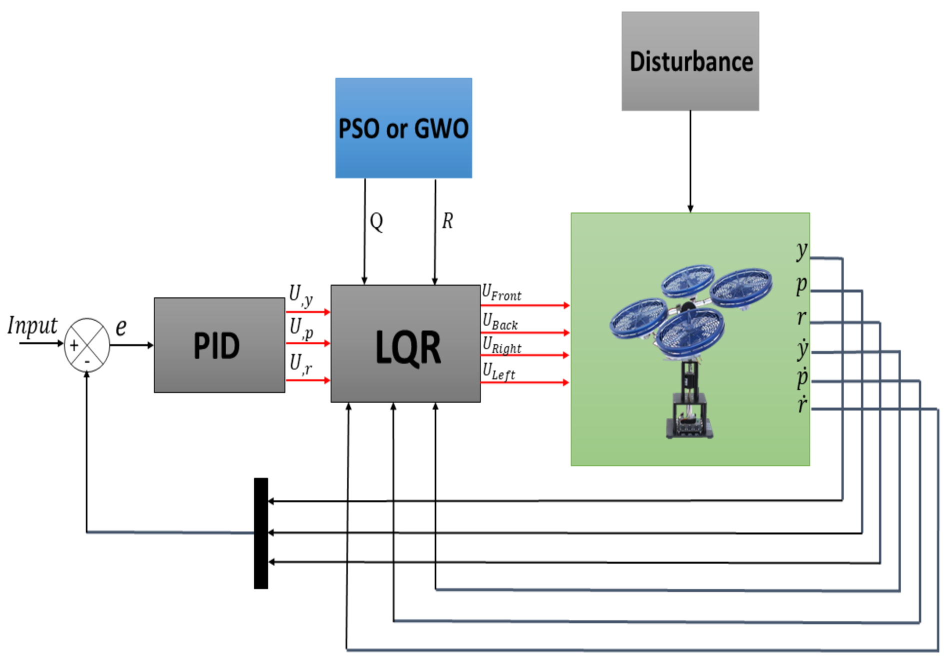

Figure 1. Quadcopter Attitude Control Diagram

The PID-LQR controller combines a PID control loop with a Linear Quadratic Regulator (LQR) for precise attitude stabilization of the quadcopter. The PID loop addresses error correction for roll, pitch, and yaw angles, while the LQR uses optimized Q and R matrices to compute the feedback gain K, minimizing a cost function of state error and control effort. This setup, implemented in Simulink, ensures optimal performance and robust disturbance rejection.

In PSO, the optimization starts by initializing a population of particles, each representing a potential Q matrix for the LQR controller. The fitness of each particle is evaluated using the LQR cost function, and each particle tracks its personal best position (pBest) and the global best position (gBest). The particles update their velocity and position based on their own pBest and the global gBest, balancing exploration and exploitation. This iterative process continues until a stopping condition is met, and the global best position represents the optimal Q matrix for the LQR controller.

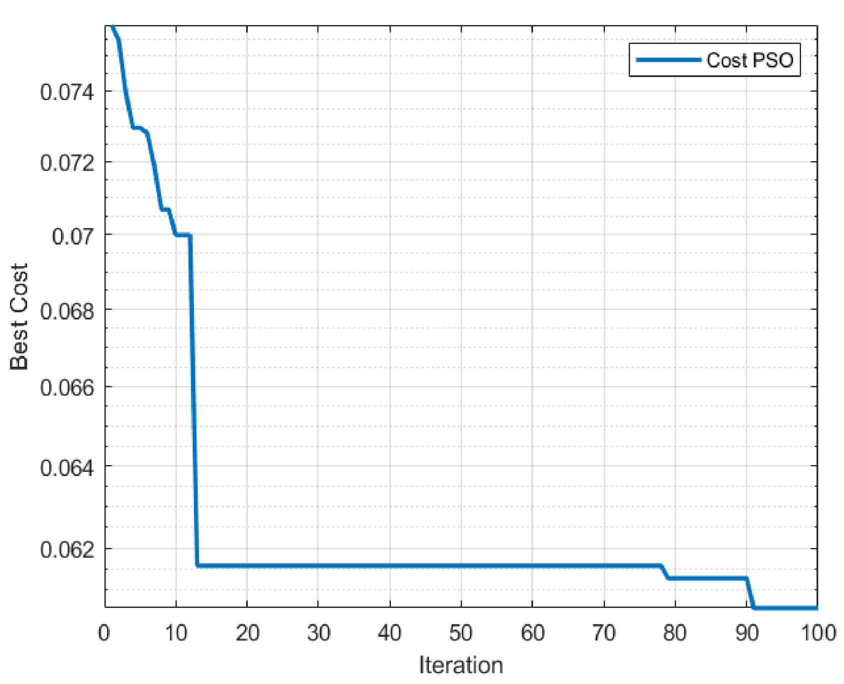

Figure 2. PSO Cost Function Minimization

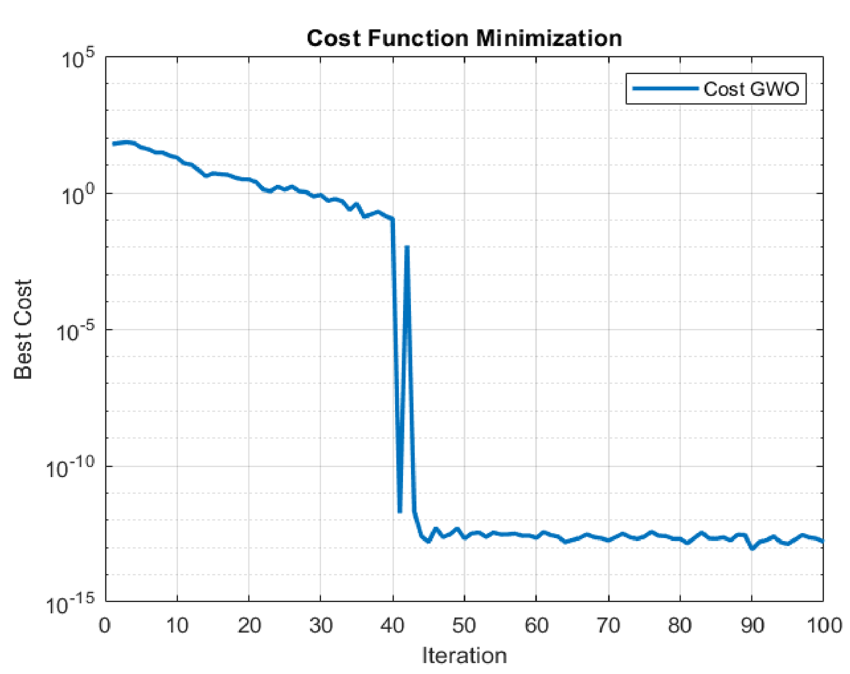

Figure 3. GWO Cost Function Minimization

GWO begins by initializing a population of wolves, where each wolf represents a potential Q matrix for the LQR controller. The fitness of each wolf is evaluated, and the top three wolves—Alpha, Beta, and Delta—serve as leaders, guiding the rest of the population. The wolves update their positions based on the leaders, with the influence of the Alpha, Beta, and Delta wolves gradually decreasing over time. This iterative process continues until a stopping criterion is met, at which point the Alpha wolf's position gives the optimal Q matrix for the LQR controller.

RESULTS & DISCUSSION

Figure 4 illustrates the step response of 10° for the Yaw, Pitch, and Roll angles using controllers optimized by PSO and GWO. The PSO-based controller exhibits a slight delay compared to the GWO-based controller in the initial transient response. However, it achieves the steady-state faster for all three angles. Notably, both optimization methods effectively track the desired step input without introducing overshoot or steady-state error, demonstrating their reliability in maintaining system stability and accuracy.

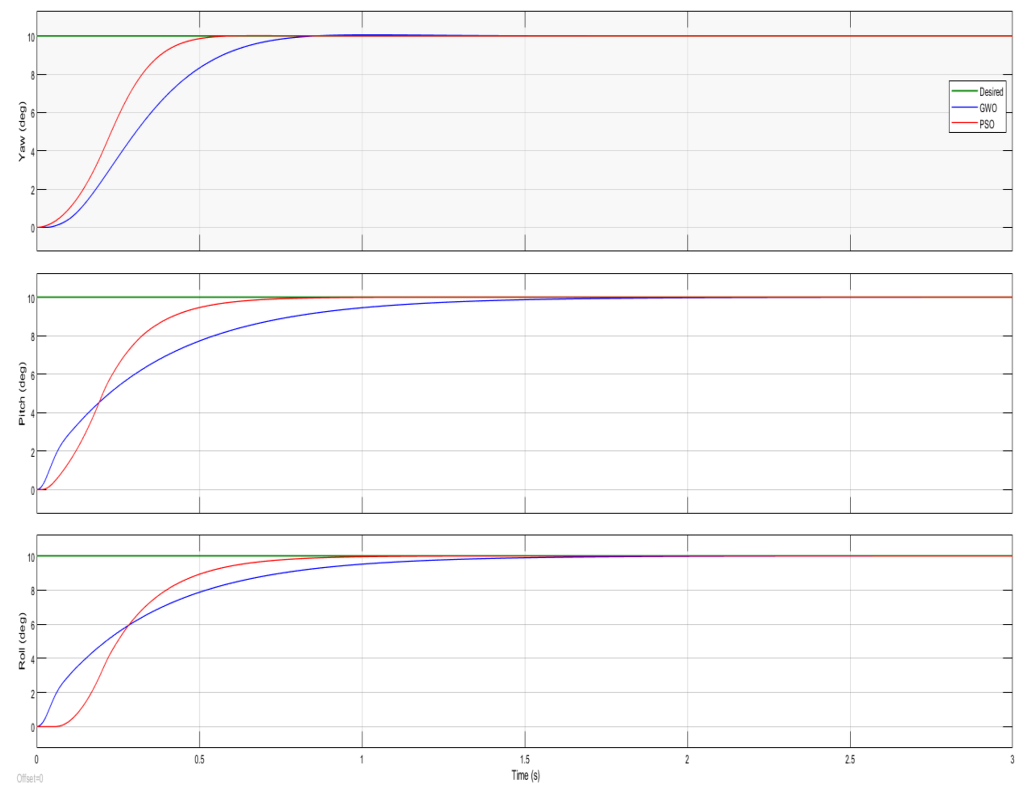

Figure 4. Step Response of Yaw, Pitch, and Roll

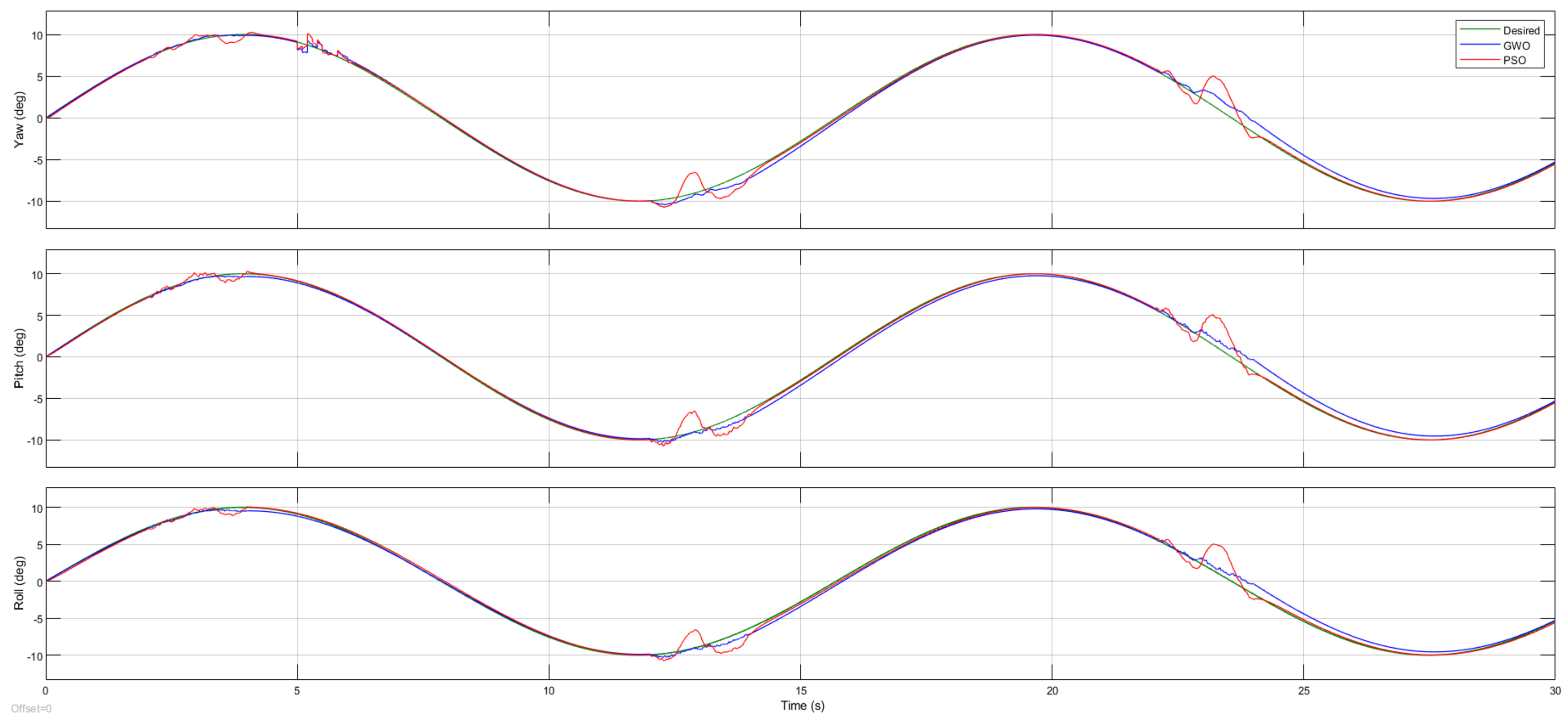

Figure 5. Trajectory Tracking Performance under Disturbances for Yaw, Pitch, and Roll

The figure shows trajectory tracking for the Yaw, Pitch, and Roll angles under disturbances at 2, 12, and 22 seconds with increasing magnitude. These disturbances mimic real-world challenges like wind gusts or signal noise. While both PSO and GWO-based controllers maintain satisfactory performance, GWO excels in disturbance rejection, limiting deviations to 1-2 degrees. PSO, however, recovers faster after disturbances. This highlights a trade-off between disturbance rejection and recovery speed, important for selecting the right controller for specific conditions.

The voltage response of the front motor highlights key differences: the GWO-based controller frequently saturates with sharp voltage spikes, aiming for high trajectory accuracy, while the PSO-based controller shows smoother voltage variations with less pronounced saturation, suggesting a balance between control effort and energy efficiency.

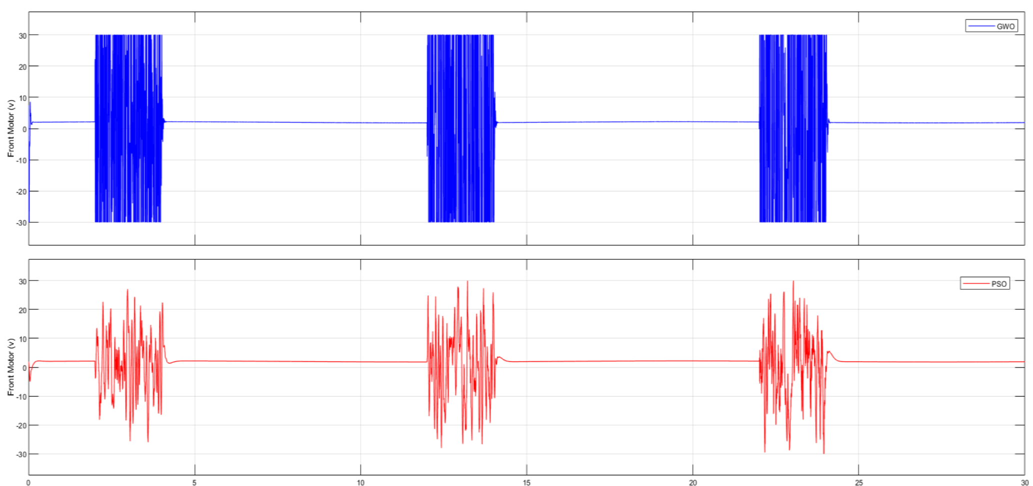

Figure 6. Front Motor Voltage During Trajectory Tracking for GWO and PSO Controllers

CONCLUSION

This work compared PSO and GWO-based controllers for quadcopter attitude stabilization under disturbances. GWO showed superior disturbance rejection with minimal deviation but experienced more voltage saturation, while PSO exhibited smoother control signals and faster stabilization after disturbances. These results highlight the trade-offs between precision and response speed in UAV control optimization.

FUTURE WORK / REFERENCES

1. Shauqee, M. N., Rajendran, P., & Suhadis, N. M. (2021). Proportional double derivative linear quadratic regulator controller using improved grey wolf optimization technique to control quadcopter. *Applied Sciences*, *11*(6), 2699.
2. Pawłowski, P., & Konatowski, S. (2020, February). Linear controller design with the use of PSO algorithm for UAV trajectory tracking. In *Radioelectronic Systems Conference 2019* (Vol. 11442, pp. 315-330). SPIE.