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Research Article

Improving the energy consumption of a quadrotor for soft landings on a platform using the Gray Wolf Optimization Algorithm

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Extended Abstract:

The increasing integration of Unmanned Aerial Vehicles (UAVs), specifically quadrotors, into various civilian and commercial domains, such as precision agriculture, infrastructure inspection, and last-mile delivery, has intensified the focus on their operational efficiency and flight endurance. A primary limitation of these electrically powered vehicles is their finite onboard energy storage, which is almost exclusively supplied by batteries. The energy capacity and weight of these batteries are fundamentally linked; a larger battery provides a longer flight time but simultaneously increases the vehicle's gross weight, which in turn escalates the power required for flight, creating a self-defeating cycle. This research, therefore, identifies a critical engineering challenge: optimizing the energy consumption of a quadrotor during its most demanding maneuver—the controlled, soft landing on a fixed platform. Reducing the energy expended during this phase not only directly extends the remaining available flight time for the mission but also opens a crucial design pathway for future platforms: the use of smaller, lighter, and more energy-dense batteries, which would lead to a lighter overall vehicle with improved agility and efficiency.

To address this challenge, the paper proposes and validates a novel hybrid control strategy that synergistically combines the robustness of Sliding Mode Control (SMC) with the powerful optimization capabilities of the Gray Wolf Optimizer (GWO) meta-heuristic algorithm. The core of the methodology lies in the design of a sophisticated controller that can navigate the highly nonlinear, coupled, and underactuated dynamics of the quadrotor while simultaneously minimizing an energy-based cost function. The quadrotor's mathematical model is established using a six-degree-of-freedom representation derived from Newton-Euler equations, which accurately captures its translational and rotational movements in 3D space. This model is then decomposed into two subsystems for control design: a fully actuated subsystem governing the three positional degrees of freedom (X, Y, Z) and an underactuated subsystem managing the three angular rotations (roll, pitch, yaw). This decoupling simplifies the controller design while respecting the physical constraints of the system.

The foundation of the control architecture is a classical Sliding Mode Controller (SMC). SMC is chosen for its renowned ability to enforce a desired trajectory by driving the system's state onto a predefined "sliding surface" and maintaining it there, despite the presence of model uncertainties and external disturbances—a common scenario in real-world UAV operations due to wind gusts and aerodynamic effects. The controller is designed with a specific reference landing trajectory, modeled as a third-order polynomial, which ensures a smooth and controlled descent from the initial hover

position to the target platform, terminating with zero velocity to achieve the "soft" landing criterion. However, a well-known drawback of classical SMC is the "chattering" phenomenon—a high-frequency oscillation around the sliding surface caused by the discontinuous signum function in the control law. This chattering is not only detrimental to the physical actuators but also represents a significant and unnecessary source of energy dissipation, which is the antithesis of the paper's primary objective.

The key innovation of this work is the introduction of the Gray Wolf Sliding Mode Control (GWOSMC) algorithm. To eliminate chattering and, more importantly, to minimize energy consumption, the authors replace the standard signum function with a smooth hyperbolic tangent (tanh) function. While this reduces chattering, the performance of the SMC is now heavily dependent on its set of tunable parameters, including the sliding surface gains and the tanh function’s boundary layer thickness. Traditionally, these parameters are selected through a tedious and often suboptimal trial-and-error process. The paper’s central contribution is the application of the GWO algorithm to intelligently and automatically tune these 16 critical control parameters.

The Gray Wolf Optimizer is a nature-inspired meta-heuristic algorithm that mimics the social hierarchy and cooperative hunting behavior of gray wolves. In this algorithm, the "alpha" wolf represents the best solution found so far, with "beta" and "delta" being the second and third best, respectively. The rest of the "pack" (the "omega" wolves) follows these leaders to explore the solution space. By mathematically modeling the processes of encircling prey, hunting, and attacking, GWO efficiently searches for the global optimum of a given objective function. In the context of this research, the objective function (or cost function) is defined as a combination of the root mean square (RMS) tracking errors for both position and velocity along the three translational axes, along with a direct term representing the total control energy consumed during the landing maneuver. The GWO algorithm’s task is to find the set of 16 control parameters that minimizes this composite cost function.

The performance of the proposed GWOSMC controller is rigorously evaluated through a series of MATLAB/Simulink simulations. The results are systematically compared against a benchmark classical SMC controller whose parameters were tuned manually. The findings are compelling and quantitatively demonstrate the superiority of the hybrid approach. Both controllers successfully guide the quadrotor to the target platform, validating their tracking capability. However, the GWOSMC controller achieves this with dramatically reduced control effort. The simulation results, as presented in the paper’s Table 3, reveal that the RMS position and velocity errors are lower for the GWOSMC, indicating a more precise and smoother trajectory. Crucially, the energy consumption metric provides the most significant validation of the research’s core hypothesis. The classical SMC controller consumes a total of 677.640 Mega-Joules (MJ) of control energy for the 10-second landing phase, while the GWOSMC controller consumes only 10.139 MJ. This represents a remarkable energy reduction of approximately 98.5%, which the paper quantifies as a "22-fold improvement" (referring to the inverse ratio of the energy consumptions).

This extraordinary reduction in energy expenditure has profound practical implications. It directly translates to the ability to use a much smaller battery for the same mission profile, thereby reducing the vehicle’s weight and cost. Furthermore, the control signals generated by the GWOSMC are demonstrably smoother, with significantly lower initial oscillation amplitudes, which protects the motors and power electronics from undue stress and wear. The paper also implicitly validates the stability of the closed-loop system. By leveraging the Lyapunov stability theorem—a standard method for proving the stability of nonlinear control systems—the authors ensure that the quadrotor’s states will asymptotically converge to the desired trajectory, guaranteeing a stable and reliable landing. In conclusion, this research successfully bridges the gap between robust nonlinear control theory and advanced computational optimization. It provides a concrete, validated, and highly effective methodology for enhancing the energy efficiency of quadrotor UAVs, with a specific and impactful application to the critical soft-landing problem. The proposed GWOSMC framework offers a significant contribution to the field of aerial robotics by directly addressing a key bottleneck in UAV operational endurance and performance.

Keywords: Quadrotor landing, sliding mode control, gray wolf algorithm, optimization, Lyapunov stability

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