Hybrid Fractional-Order PID and Sliding Mode Control for Robust Stabilization of Quadrotor UAVs

Hybridní řízení na bázi PID neceločíselného řádu a klouzavého režimu pro robustní stabilizaci bezpilotních letounů typu kvadrokoptéra

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Abstract:

Unmanned Aerial Vehicles (UAVs), particularly quadrotor systems, have gained significant attention due to their wide range of applications, including surveillance, environmental monitoring, inspection, and autonomous navigation. Despite their advantages, quadrotor UAVs exhibit inherently nonlinear, coupled, and underactuated dynamics, which make control design a challenging task, especially in the presence of external disturbances and system uncertainties. Classical control approaches such as proportional–integral–derivative (PID) controllers are widely used due to their simplicity and ease of implementation. However, their performance often degrades under uncertain and dynamic operating conditions. Sliding Mode Control (SMC) offers strong robustness against disturbances and model uncertainties, but it suffers from the chattering phenomenon, which can negatively affect system performance. Fractional-order control has emerged as an advanced control methodology that extends classical integer-order controllers by incorporating non-integer derivatives and integrals. This approach provides additional degrees of freedom and memory characteristics, enabling improved system performance and flexibility. Recent studies have demonstrated the effectiveness of fractional-order PID controllers in enhancing system performance and efficiency. Similarly, fractional-order sliding mode control approaches have shown improved robustness in nonlinear systems. Motivated by these developments, this research proposes a hybrid control framework that integrates Fractional-Order PID (FOPID) and Sliding Mode Control (SMC) to achieve robust stabilization and improved performance for quadrotor UAV systems.

The control of quadrotor UAVs faces several challenges:

- Nonlinear and strongly coupled system dynamics

- Sensitivity to external disturbances such as wind - Parametric uncertainties in system modeling

- Chattering effects in robust control methods

- Limited flexibility in classical control approaches

Although fractional-order controllers enhance flexibility and sliding mode control improves robustness, their integration into a unified framework remains insufficiently explored for quadrotor UAV systems. Previous works have demonstrated the advantages of fractional-order PID control, as well as the robustness of fractional-order sliding mode control. Additionally, hybrid strategies combining these techniques have shown improved

performance in other engineering systems. However, there is still a lack of comprehensive studies focusing on hybrid FOPID–SMC control for quadrotor UAV stabilization, particularly with optimization and stability guarantees. This research aims to address this gap.

General Research Objective: To develop a robust hybrid control framework based on fractional-order PID and sliding mode control for stabilization and trajectory tracking of quadrotor UAVs.

Specific Research Objectives:

- Develop a nonlinear dynamic model of a quadrotor UAV - Design a Fractional-Order PID (FOPID) controller

- Develop a Sliding Mode Control (SMC) scheme with reduced chattering

- Integrate FOPID and SMC into a hybrid control structure

- Optimize controller parameters using intelligent optimization techniques

- Perform stability analysis using Lyapunov-based methods

- Validate the proposed approach through simulation and comparative analysis

Literature:

[1] B. Mohanty and S. Mohanty, “A Novel State Machine-Fractional Order PID Control Strategy for Energy Management Framework to Optimize the Consumption From Fuel Cell in DC Microgrid,” IEEE Access, vol. 12, pp. 136160–136182, 2024.

[2] S. Konar, M. D. Patil, and V. A. Vyawahare, “Design of a Fractional Order Sliding Mode Controller for Depth Control of AUV,” Proceedings of the Second International Conference on Intelligent Computing and Control Systems, 2018, pp. 1342–1345.

[3] C. Abdelghani, C. Lakhdar, A. Salem, B. M. Djameleddine, and M. Lakhdar, “Robust Design of Fractional Order PID Sliding Mode Based Power System Stabilizer via a Bat Algorithm,” Proceedings of the International Workshop on Recent Advances in Sliding Modes, 2015.

[4] S. M. Ghamari, D. Habibi, and A. Aziz, “Robust Adaptive Fractional-Order PID Controller Design for High-Power DC-DC Dual Active Bridge Converter Enhanced Using Multi-Agent Deep Deterministic Policy Gradient Algorithm,” Energies, vol. 18, no. 12, 2025.

[5] M. Qin, S. Dian, B. Guo, X. Tao, and T. Zhao, “Fractional-Order Sliding Mode Controller for Mobile Robot Trajectory Tracking Under Actuator Fault,” Systems Science & Control Engineering, vol. 10, no. 1, pp. 312–324, 2022.

[6] A. M. Aghazamani and M. Khodabandeh, “Fault-tolerant adaptive fractional order sliding mode control for a quadrotor using disturbance observer,” Journal of Control and Decision, vol. 11, no. 4, pp. 689–706, 2024.

[7] M. Al-Dhaifallah, F. M. Al-Qahtani, S. Elferik, and A.-W. A. Saif, “Quadrotor Robust Fractional-Order Sliding Mode Control in Unmanned Aerial Vehicles for Eliminating External Disturbances,” Aerospace, vol. 10, no. 8, 665, 2023.

[8] V. Borja-Jaimes, A. Coronel-Escamilla, R. F. Escobar-Jiménez, M. Adam-Medina, G. V. Guerrero-Ramírez, E. M. Sánchez-Coronado, and J. García-Morales, “Fractional-Order Sliding Mode Observer for Actuator Fault Estimation in a Quadrotor UAV,” Mathematics, vol. 12, no. 8, 1247, 2024.

[9] Z. Zhang and H. Zhang, “Fractional-Order Sliding Mode with Active Disturbance Rejection Control for UAVs,” Applied Sciences, vol. 15, no. 2, 556, 2025.

[10] A. Benaddy, M. Labbadi, K. Elyaalaoui, and M. Bouzi, “Fixed-Time Fractional-Order Sliding Mode Control for UAVs under External Disturbances,” Fractal and Fractional, vol. 7, no. 11, 775, 2023.