



OTIMIZAÇÃO DA EFICIÊNCIA ENERGÉTICA EM DRONES DE PULVERIZAÇÃO AGRÍCOLA COM BASE EM CONTROLADORES PID FRACIONÁRIOS E ALGORITMO GENÉTICO

OPTIMIZING ENERGY EFFICIENCY IN AGRICULTURAL SPRAYING DRONES BASED ON FRACTIONAL-ORDER PID CONTROLLERS AND GENETIC ALGORITHM

Authors: Heictor Alves de Oliveira Costa¹; Fernando José Von Zuben²

¹Universidade Estadual de Campinas (UNICAMP), h290881@dac.unicamp.br

²Universidade Estadual de Campinas (UNICAMP), vonzub@unicamp.br

RESUMO

A viabilidade da agricultura de precisão na agricultura familiar está intrinsecamente ligada à eficiência operacional e energética dos equipamentos, especialmente quando dependem de fontes renováveis no local, como painéis fotovoltaicos. Este trabalho aborda o desafio de maximizar a eficiência energética de drones de pulverização através de uma otimização de controle avançada. A metodologia emprega um Algoritmo Genético (AG) para otimizar e comparar dois tipos de controladores: um Proporcional-Integral-Derivativo (PID) convencional e um PID de Ordem Fracionária (FOPID). A otimização visa minimizar uma função de custo que modela o consumo de energia e o tempo de voo. Os resultados da simulação demonstram que o controlador FOPID alcança uma redução de 3,1% no custo operacional por hectare em comparação com o PID convencional. Análises dos perfis de aceleração revelam que o FOPID evita os picos ruidosos e sequenciais característicos do PID, resultando em um menor esforço de controle geral e, conseqüentemente, menor consumo de energia. O estudo conclui que a otimização de software avançada, especificamente com controladores FOPID, oferece uma solução energeticamente eficiente que promove a sustentabilidade na agricultura familiar.

Palavras-chave: Eficiência Energética; Drone Agrícola; Controle de Ordem Fracionária; Algoritmo Genético; Agricultura de Precisão.



ABSTRACT

The viability of precision agriculture in family farming is intrinsically linked to the operational and energy efficiency of equipment, especially when relying on on-site renewable sources like photovoltaic panels. This paper addresses the challenge of maximizing the energy efficiency of spraying drones through advanced control optimization. The methodology employs a Genetic Algorithm (GA) to optimize and compare two controller types: a conventional Proportional-Integral-Derivative (PID) and a Fractional-Order PID (FOPID). The optimization aims to minimize a cost function that models energy consumption and flight time. Simulation results demonstrate that the FOPID controller achieves a 3.1% reduction in operational cost per hectare compared to the conventional PID. Analysis of the acceleration profiles reveals that the FOPID avoids the noisy and sequential peaks, characteristic of the PID, resulting in lower overall control effort and, consequently, reduced energy consumption. The study concludes that advanced software optimization, specifically with FOPID controllers, offers an energy-efficient solution that promotes sustainability in family farming.

Keywords: Energy Efficiency; Agricultural Drone; Fractional-Order Control; Genetic Algorithm; Precision Agriculture.

1 INTRODUCTION

The agricultural sector is a cornerstone of the global economy but also a significant consumer of energy (MAJEED et al., 2023). The increasing integration of renewable energy sources, such as on-farm photovoltaic (PV) systems, is pivotal for enhancing sustainability and reducing operational costs, particularly for family farming operations (GORJIAN et al., 2020). In this context, Unmanned Aerial Vehicles (UAVs), or drones, have emerged as a transformative technology in precision agriculture (SETIAWAN et al., 2025). However, the operational viability of these drones is intrinsically linked to their energy efficiency and power consumption, as limited battery life poses a significant constraint (REZOUG; IQBAL; NEMRA, 2025).

The central challenge this paper addresses is the optimization of a drone's flight dynamics to minimize energy expenditure during agricultural spraying missions. This is not merely an economic consideration but a crucial factor for sustainability, as higher efficiency translates to less demand on limited, locally-generated renewable energy. While Proportional-Integral-Derivative (PID) controllers are widely used for UAV stabilization, their integer-order structure can be restrictive when fine-tuning for optimal energy use (BAHARUDDIN; BASRI, 2023; AL-MAHTURI et al., 2020). Abrupt and aggressive control actions can lead to inefficient power usage and mechanical wear (SHANKARAN et al., 2022).

This study explores the potential of Fractional-Order PID (FOPID) controllers, which generalize the integral and derivative terms to non-integer orders (λ and μ), offering additional degrees of freedom (PODLUBNY, 1999). This enhanced flexibility allows for a more precise



shaping of the system's dynamic response. The scientific gap lies in applying this advanced control strategy, optimized via a Genetic Algorithm (GA) and guided by an intelligent path planner (Probabilistic Roadmap), to specifically target energy efficiency in an agricultural context. We hypothesize that this software-driven approach can yield a more efficient control system, characterized by smoother behavior and reduced control effort.

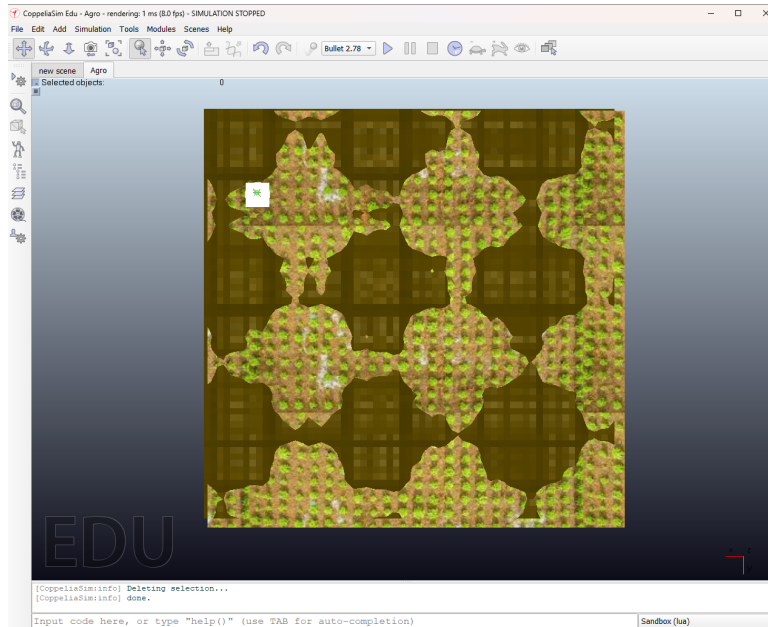
2 METHODOLOGY

The methodology integrates path planning and control optimization within a high-fidelity simulation environment. The objective is to create an energy-efficient flight plan for a drone operating in a complex agricultural setting.

2.1 Path Planning in a Simulated Environment

The process begins in the CoppeliaSim environment, which hosts a virtual agricultural terrain complete with cultivation areas and non-navigable obstacles, as shown in Figure 1. An initial reconnaissance flight allows onboard sensors to gather data, from which a map of the area is constructed.

Figure 1: Simulation environment in CoppeliaSim showing agricultural terrain.



Using this map, the Probabilistic Roadmap (PRM) algorithm ('mobileRobotPRM' in MATLAB) generates a graph of all possible safe paths, as seen in Figure 2. The PRM is highly effective for environments with complex obstacle geometries (KAVRAKI et al., 1996; ARNALDO et al., 2024). A specific flight path is then calculated from this roadmap. Figure 3 shows a



partial segment of a trajectory, while Figure 4 illustrates a complete coverage path synthesized from multiple such segments.

Figure 2: Probabilistic Roadmap (PRM) generated over the free space.

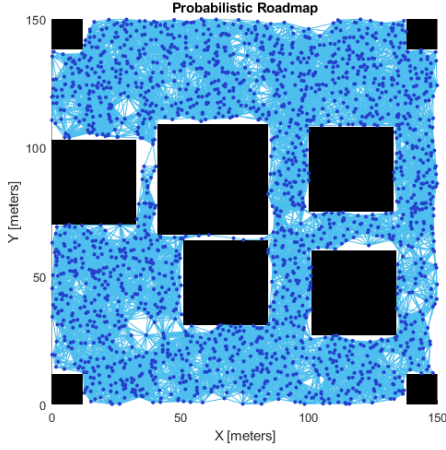
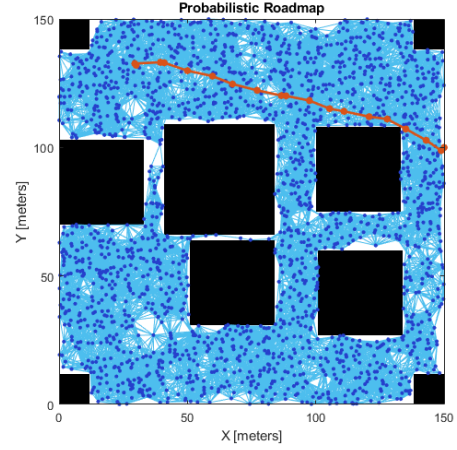


Figure 3: A partial path segment calculated using the PRM.



2.2 Controller Design and Optimization

With a defined trajectory, a Genetic Algorithm (GA) optimizes the drone's control system for energy efficiency (KHUWAJA et al., 2018). The GA tunes the parameters of two different controllers for comparison: a conventional PID and a Fractional-Order PID (FOPID). The FOPID controller's $PI^\lambda D^\mu$ structure offers greater tuning flexibility, which can lead to smoother responses and improved robustness (ZHUO-YUN et al., 2020; FAREH, 2019).

The GA's goal is to minimize a cost function, J , that models the trade-offs of a mission:

$$J = \int_0^T \left[w_1 \sqrt{\dot{x}(t)^2 + \dot{y}(t)^2 + \dot{z}(t)^2} + w_2 t + w_3 P(p(t)) + w_4 \frac{m(t)}{B(t)} \right] dt \quad (1)$$

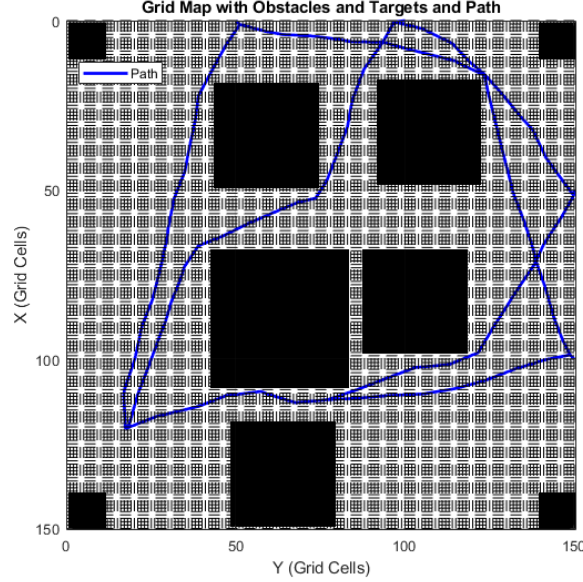
The terms in the function represent weighted costs for path length (energy), flight time, obstacle risk, and battery usage. Critically, the drone's mass, $m(t)$, decreases as it sprays, and the battery level, $B(t)$, is depleted by control effort, making the simulation physically realistic.

2.3 Solution Evaluation Structure

We use GA optimization to find optimal PID tuning by treating cost function solutions as population individuals that evolve across generations. Each solution represents a specific controller configuration. To conserve resources, only the best solution from each optimization run is tested in CoppeliaSim.



Figure 4: The complete, synthesized coverage path on the grid map.



3 RESULTS AND DISCUSSION

Following the presented methodology, each simulation took around 6 minutes (2 minutes of optimization and 4 minutes of flight simulation). To obtain reliable data, the optimization/simulation combination was performed 45 times.

The optimization process yielded distinct performance profiles for the PID and FOPID controllers. The analysis focuses on both the overall mission cost and the specific characteristics of the control effort.

3.1 Energy Efficiency and Operational Cost

The GA was executed to minimize the cost function J for both controllers. The resulting dimensionless costs were:

- **Regular PID Controller:** $J_{PID} = 2.256916 \times 10^4$
- **Fractional-Order PID Controller:** $J_{FOPID} = 2.186916 \times 10^4$

Using a conversion methodology calibrated against the real-world operational costs of a drone (including energy, battery depreciation, and maintenance), these abstract values were translated into a tangible metric. The analysis, detailed in Table 1, shows that the FOPID controller achieves a **3.1% reduction in operational cost per hectare**.



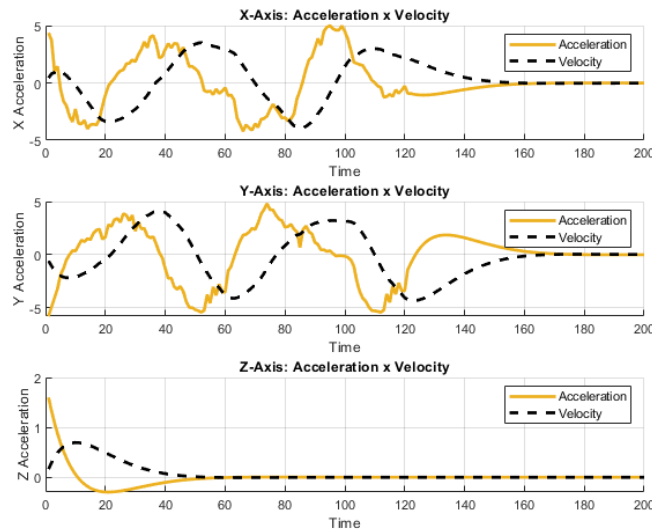
Table 1: Cost conversion from dimensionless J to \$/Hectare.

Metric	Regular PID	FOPID
Optimized J Cost (adimensional)	22,569.16	21,869.16
Real Mission Cost [\$]	\$2.66	\$2.58
Operational Cost [\$ /ha]	\$0.89	\$0.86
Improvement vs. PID	—	3.1%

3.2 Control Effort and Acceleration Profile Analysis

To understand this efficiency gain, acceleration profiles of both controllers were analyzed during the initial flight moments—the most turbulent phase when transitioning from stationary to cruise speed. Figure 5 shows the PID controller’s acceleration and velocity, while Figure 6 displays the same for the FOPID controller.

Figure 5: Acceleration and velocity profiles for the standard PID controller.



Visual comparison shows the standard PID controller (Figure 5) produces a noisy acceleration profile with multiple peaks. These represent abrupt corrections, causing overshoot and repeated acceleration/deceleration cycles. This control approach stresses mechanical components and drains battery with high peak current demands.

Conversely, the FOPID controller (Figure 6) delivers smoother acceleration. While velocity profiles remain similar across both controllers, FOPID requires less abrupt effort from the drone’s components, preventing oscillations typical in PID responses. This characteristic of fractional-order systems reduces total control effort, with the smoother acceleration pattern yielding a 3.1% efficiency improvement.

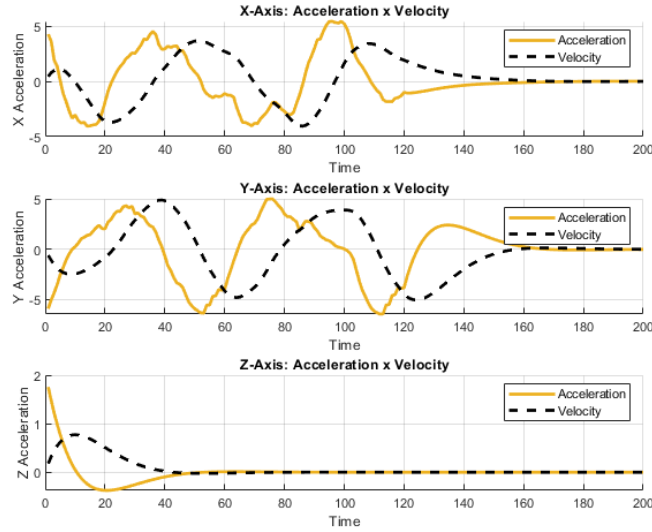


Figure 6: Acceleration and velocity profiles for the FOPID controller.

4 CONCLUSIONS

This paper successfully demonstrated that an advanced, software-driven approach can significantly enhance the energy efficiency of agricultural drones. By employing a Genetic Algorithm to optimize a Fractional-Order PID controller and guiding it with a path from a Probabilistic Roadmap planner, we achieved a more efficient and smoother flight control system compared to a conventional PID controller.

The primary finding is that the FOPID controller yields a 3.1% reduction in operational cost per hectare. It is a direct consequence of a more effective control strategy. The analysis of acceleration profiles showed that the FOPID controller avoids energy-intensive, high-amplitude corrections in favor of more subtle, high-frequency adjustments, resulting in less mechanical stress and lower overall power consumption.

For the family farmers relying on renewable energy, this efficiency gain is critical. It translates to more area covered per battery charge, greater operational autonomy, and reduced strain on local energy systems. This study validates that focusing on software intelligence, particularly advanced control theory, is a powerful pathway to creating sustainable, efficient, and accessible technology for modern agriculture.

Acknowledgment

This work was supported by Ericsson Telecomunicações Ltda., and by the São Paulo Research Foundation (FAPESP), grant 2021/00199-8, CPE SMARTNESS.

This research has been supported by grants from CNPq (process no. 308793/2022-6).



References

- AL-MAHTURI, A. et al. Pid controller tuning for a quadcopter using meta-heuristic algorithms. *Applied Sciences*, MDPI, v. 10, n. 21, p. 7826, 2020.
- ARNALDO, C. G. et al. Path planning for unmanned aerial vehicles in complex environments. *Drones*, v. 8, n. 7, 2024. ISSN 2504-446X.
- BAHARUDDIN, A.; BASRI, M. A. M. Self-tuning pid controller for quadcopter using fuzzy logic. *International Journal of Robotics and Control Systems*, v. 3, n. 4, p. 728–748, 2023. ISSN 2775-2658.
- FAREH, R. Sliding mode fractional order control for a single flexible link manipulator. *International Journal of Mechanical Engineering and Robotics Research*, v. 8, n. 2, p. 228–232, mar 2019.
- GORJIAN, S. et al. Chapter 6 - on-farm applications of solar pv systems. In: GORJIAN, S.; SHUKLA, A. (Ed.). *Photovoltaic Solar Energy Conversion*. [S.l.]: Academic Press, 2020. p. 147–190. ISBN 978-0-12-819610-6.
- KAVRAKI, L. E. et al. Probabilistic roadmaps for path planning in high-dimensional configuration spaces. *IEEE Transactions on robotics and automation*, IEEE, v. 12, n. 4, p. 566–580, 1996.
- KHUWAJA, K. et al. Pid controller tuning optimization with genetic algorithms for a quadcopter. In: . [S.l.: s.n.], 2018. v. 5, n. 1, p. 1–7.
- MAJEED, Y. et al. Renewable energy as an alternative source for energy management in agriculture. *Energy Reports*, v. 10, p. 344–359, 2023. ISSN 2352-4847.
- PODLUBNY, I. Fractional-order systems and $\pi^{\lambda}d^{\mu}$ -controllers. *IEEE Transactions on Automatic Control*, v. 44, n. 1, p. 208–214, 1999.
- REZOUG, A.; IQBAL, J.; NEMRA, A. Dual fopid-neural network controller based on fast grey wolf optimizer: application to two-inputs two-outputs helicopter. *Systems Science & Control Engineering*, Taylor & Francis, v. 13, n. 1, p. 2449156, 2025.
- SETIAWAN, M. et al. A comparative study of pid, fopid, isf, smc, and flc controllers for dc motor speed control with particle swarm optimization. *International Journal of Robotics and Control Systems*, v. 5, n. 1, p. 640–660, 2025. ISSN 2775-2658.
- SHANKARAN, V. P. et al. Improved performance in quadrotor trajectory tracking using mimo pi-d control. *IEEE Access*, v. 10, p. 110646–110660, 2022.
- ZHUO-YUN, N. et al. Fractional-order pid controller design for time-delay systems based on modified bode's ideal transfer function. *IEEE Access*, v. 8, p. 103500–103510, 2020.