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GRAPHICAL ABSTRACT

ANALYSIS OF FEEDFORWARD CONTROL APPROACHES FOR AUTONOMOUS QUADCOPTERS

1. PROBLEM AND MOTIVATION

- Bridging the gap between trajectory-based feedforward control (academic literature) and dynamic inversion (practical flight controllers like Ardupilot).
- Classical methods aim for zero tracking error by anticipating reference trajectories.
- Practical implementations prioritize actuator smoothness and effort prediction.
- Aggressive feedforward tuning may degrade physical performance and stability.

OBJECTIVE:
To comparatively evaluate the effects of velocity and acceleration feedforward gains on the performance of a quadcopter in the vertical (z-axis) tracking task.

2. METHODOLOGY

System:
Simulated quadcopter (z-axis analysis).

Feedforward Approaches:
- Classical trajectory-based feedforward
- Dynamic inversion (Ardupilot-like)

Scenarios:
162 scenarios with different combinations of velocity and acceleration feedforward gains.

Performance Metrics:
- Integral Absolute Error (IAE)
- Integral of Squared Input (ISU)
- Total Variation (TV)

Comparative analysis conducted to evaluate tracking accuracy, control effort, and actuator smoothness.

3. FEEDFORWARD ARCHITECTURES

Classical Trajectory-Based Feedforward

Goal	→	Zero tracking error
Strategy	→	Anticipates reference trajectories
Priority	→	Tracking accuracy
Effect	→	Sensitive to high acceleration gains

Dynamic Inversion (Ardupilot-like)

Goal	→	Stability and smooth actuator behavior
Strategy	→	Effort prediction and actuator smoothness
Priority	→	Robustness and stability
Effect	→	More conservative performance

Architectural differences lead to distinct performance trade-offs.

4. KEY FINDINGS

- The classical approach reduces position tracking error by up to ten times compared to the dynamic inversion approach.
- However, it induces severe velocity overshoots (up to 36.1%).
- High acceleration feedforward gains cause extreme actuator chattering and increased control effort.
- Aggressive feedforward tuning degrades physical performance and may compromise stability.
- The dynamic inversion (Ardupilot-like) approach provides greater stability and smoother actuator behavior, with lower overshoot (max. 5.6%).

CONCLUSION:
Stability-focused architecture adopted by available flight controllers is validated.

5. ANALYZED SCENARIOS

Total Scenarios:
162 combinations of feedforward velocity and acceleration gains.

Excitation:
Step and jerk-limited motion profiles in the z-axis.

Evaluated Aspects:
Tracking accuracy, control effort, and actuator smoothness.

Goal:
Understand the impact of feedforward parameters on physical performance.

6. PERFORMANCE EVALUATION

IAE — Integral Absolute Error
Measures the tracking error. Lower values indicate better tracking performance.

ISU — Integral of Squared Input
Represents the control effort. Higher values indicate greater energy consumption.

TV — Total Variation
Measures the smoothness of the control signal. Lower values indicate less actuator chattering.

These metrics provide a comprehensive assessment of the control strategies.

7. MAIN TAKEAWAYS

- Trajectory-based feedforward improves tracking accuracy but at the cost of higher overshoot and control effort.
- Acceleration feedforward gains must be carefully tuned to avoid actuator stress.
- Feedforward is beneficial, but excessive gains can harm system performance.
- Dynamic inversion provides a robust and practical solution for real-world flight controllers.
- Trade-off between accuracy and stability is crucial in control design.

Balanced design ensures reliable and efficient operation of autonomous quadcopters.

8. IMPLICATIONS AND FUTURE WORK

Practical Relevance
Supports the use of stability-focused architectures in open-source flight controllers.

Design Guidance
Provides insights for feedforward tuning and controller design in UAVs.

Future Comparisons
Encourages further studies under diverse trajectories and environmental conditions.

Broader Impact
Contributes to safer, more efficient, and reliable autonomous flight systems.

PREPRINTS
This manuscript is not a preprint.

CONFLICT OF INTEREST
The authors declare no conflict of interest.

DATA AVAILABILITY
All data supporting the results of this study are included in the article.

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