



## Advanced Control Strategies for Altitude Maintenance in Fixed-Wing UAVs During Extreme Maneuvers – A Review

Y.D. Amarasingha, Chandana Perera

Faculty of Engineering, NSBM Green University, Sri Lanka  
ydamarasingha@students.nsbm.ac.lk

Received:28 June 2025; Revised: 30 June 2025; Accepted: 06 July 2025; Available online: 10 July 2025

**Abstract:** Maintaining precise altitude during aggressive maneuvers is a significant challenge for fixed-wing UAVs, particularly in high-speed flight, aerobatic maneuvers, and extreme conditions. These aircraft need to control altitude during sharp turns, quick climbs and descents, high-G maneuvers, and aerobatic sequences that involve significant attitude changes and nonlinear aerodynamics. This review looks at the latest control methods for altitude regulation in these situations. Here, discuss classical PID loops, model-based nonlinear controllers, including INDI and sliding modes, optimal/MPC approaches, and new learning-based methods, along with strategies for actuator allocation and sensor fusion. This review pays special attention to conventional aircraft designs with traditional control surfaces and how they affect control design in extreme flight operations. Recent experimental results highlight performance. Key studies show how sophisticated controllers can achieve close altitude tracking during aggressive maneuvers, though sensor noise and aerodynamic uncertainty present limitations. This review identifies open challenges, such as creating unified high-performance controllers, improving altitude estimation during dynamic flight, and exploring promising directions for future research.

**Index Terms:** Altitude hold, Extreme maneuvers, Fixed-wing UAV, Incremental Nonlinear Dynamic Inversion (INDI)

### 1 INTRODUCTION

Fixed-wing UAVs operating in extreme flight conditions face significant challenges in maintaining precise altitude control during aggressive maneuvers [1],[2],[3]. These aircraft must execute tight turns, rapid climbs and descents, aerobatic sequences, and high-speed operations while keeping altitude within acceptable limits [4],[5]. Unlike conventional cruise flights, extreme maneuvers involve significant changes in angle of attack (AoA), quick attitude shifts, and nonlinear aerodynamic effects that can significantly affect altitude control performance [6],[7].

The flight envelope during extreme maneuvers is highly nonlinear. Aggressive turns at steep bank angles, rapid pull-ups and pushovers, aerobatic sequences, and high-G operations lead to significant variations in lift, drag, and control effectiveness [8],[9]. These swift configuration changes create considerable aerodynamic coupling and nonlinear dynamics, causing simple control laws to fail in maintaining precise altitude [10],[11]. Traditional altitude control methods, which are designed for calm flight conditions, often result in large altitude deviations during aggressive maneuvers [12],[13]. In missions that require precise flight operations, aerobatic displays, or tactical maneuvers with strict altitude limits, standard altitude-control

strategies are not sufficient [14],[15].

This review focuses on control strategies that allow for precise altitude regulation in fixed-wing UAVs during extreme maneuvers and aggressive flight operations [16],[17]. We highlight studies that address high-performance aircraft configurations and the unique challenges of extreme flight conditions [18],[19]. This review begins by reviewing control algorithms (PID, INDI, MPC/optimal, learning-based) that have been applied to altitude maintenance during aggressive flight [20],[21]. Next, we examine actuator configurations (elevators, ailerons, rudders, thrust vectoring) and how control demands are distributed among them during extreme maneuvers [22]. This review covers sensor-estimation strategies for altitude during dynamic flight conditions, as well as aerodynamic issues encountered during high-G operations [2],[3]. Key experimental studies and benchmarks are summarized. Throughout the review, it emphasizes the main contributions of recent studies in this field. This review summarizes the current state of the art and outlines promising research directions to achieve strong, high-performance altitude control during extreme flight operations [4],[5].

## 2 CONTROL ALGORITHMS FOR ALTITUDE REGULATION DURING EXTREME MANEUVERS

Traditional PID controllers struggle with nonlinearities and actuator limits during extreme maneuvers. Alternatives like INDI, sliding mode, MPC, and learning-based methods enhance robustness, constraint handling, and adaptability during those extreme maneuvers. These advanced controllers improve altitude tracking during aggressive flights by addressing aerodynamic uncertainties, fast dynamics, and control surface limitations.

### 2.1 PID Control in High-Performance Flight

In conventional fixed-wing aircraft, altitude is managed by traditional outer-loop PID controllers that adjust elevator deflection or throttle to maintain the desired altitude [24],[6],[7]. Standard autopilots use cascade architecture. The outer altitude loop commands pitch attitude or vertical speed references to inner attitude controllers. Lohani, Dixit, and Agrawal show that conventional autopilots "control the aircraft's attitude, air speed, and altitude" mainly through cascaded PID loops [24]. However, during extreme maneuvers, PID controllers face severe limitations [8],[9].

During aggressive turns, rapid attitude changes and high-G loading create considerable coupling in the altitude dynamics [10],[11]. The effectiveness of control surfaces varies significantly with changes in air speed and angle of attack, which are common in extreme maneuvers [12],[13]. PID gains that are optimized for cruise flights are not suitable during aerobatic sequences or high-G operations [14][15]. Furthermore, classical PID methods struggle with actuator saturations, nonlinear aerodynamic effects, and the rapid dynamics typical of extreme flight conditions [16],[17]. As a result, altitude tracking during tight turns, aerobatic maneuvers, or high-speed operations often shows significant errors, oscillations, or instability [18],[19].

### 2.2 Incremental Nonlinear Control (INDI) for Extreme Flight Operations

Incremental Nonlinear Dynamic Inversion (INDI) has emerged as a groundbreaking method for high-performance flight control. It is especially effective in extreme maneuvering scenarios [25],[20],[21]. Unlike traditional model-based methods, INDI linearizes, and inverts dynamics based on measured accelerations instead of detailed aerodynamic models [22]. This feature makes it particularly suitable for extreme flight conditions where aerodynamic models may not be reliable [2],[3].

Smeur, Bronz, and de Croon created INDI-based controllers that show impressive performance across the entire flight envelope [25]. Their method significantly decreases reliance on precise aerodynamic modeling,

making it resilient to the aerodynamic uncertainties that arise during extreme maneuvers [4],[5]. Tal and Karaman built on this idea with their "global incremental flight control" approach. They combined differential flatness with INDI [26]. Their controller tracks position, velocity, acceleration, jerk, and yaw rate by using feedforward of higher-order trajectory derivatives [6],[7].

The Tal-Karaman controller does not rely on extensive aerodynamic modeling. Instead, it uses INDI to compute control updates based solely on a local input-output relationship, which leads to robustness against errors in simplified aerodynamic equations [26]. Flight tests have shown exceptional performance during challenging agile maneuvers, including extreme attitude changes and aggressive flight operations [26],[8],[9]. The controller maintained precise altitude tracking even during maneuvers that would pose difficulties for traditional control methods [10],[11].

Incremental backstepping, an extension of INDI principles, has also shown potential for extreme flight applications [27],[12],[13]. Athayde, Moutinho, and Azinheira demonstrated that incremental methods deliver smooth control responses and reliable attitude tracking during dynamic flight conditions [27]. Their experimental results indicated that while perfect altitude tracking is hard to achieve due to sensor limitations, the incremental approach outperformed traditional methods [14],[15]. The authors noted that altitude tracking showed some oscillations due to sensor filtering. They suggested that applying incremental logic to the altitude loop could further enhance robustness [27],[16],[17].

### 2.3 Sliding Mode and Adaptive Control for High-G Operations

Sliding mode control strategies are designed for extreme flight conditions where quick convergence and disturbance rejection are crucial [28],[18],[19]. Wang, Zhang, Li, Chen, and Liu developed an adaptive continuous quasi-fixed-time integral terminal sliding mode controller for extreme maneuvering situations [28]. This controller combines terminal sliding mode features with adaptive estimation to ensure fixed-time convergence of tracking errors. It offers excellent robustness against the disturbances and uncertainties faced during aggressive flights [20],[21].

The sliding mode approach performs well in extreme flight scenarios because it has strong disturbance rejection capabilities that are vital for keeping altitude during high-G maneuvers [22]. The controller includes smooth reference trajectory planning to avoid actuator saturation, which is essential during extreme maneuvers when control authority may be limited [2],[3]. Simulation and flight test results showed that the sliding mode approach outperformed both standard INDI and traditional fixed-time controllers in aggressive maneuvering situations [28],[4],[5].

These strong nonlinear control techniques prove that improved sliding mode methods can provide remarkable disturbance rejection during extreme flight operations, though they come with increased controller complexity and tuning needs [6],[7]. The fixed-time convergence properties are especially valuable during quick maneuvers when traditional controllers may struggle to maintain good performance [8],[9].

### 2.4 Optimal and Model Predictive Control for Aggressive Maneuvers

Model Predictive Control (MPC) and trajectory optimization methods have been studied for managing altitude during extreme flight operations [29],[10],[11]. Banazadeh and Taymourtash investigated optimal control methods for aggressive maneuvering, focusing on time-optimal path planning while keeping altitude constraints [29]. Their research showed that treating altitude maintenance as a constrained optimization problem can lead to better performance during extreme maneuvers [12],[13].

Recently, Cheng and Pei created optimization frameworks for time-optimal maneuvering with altitude-hold constraints [30]. They introduced a "corridor" approach to manage high-order dynamics during aggressive

maneuvers, generating feasible altitude-preserving trajectories [14],[15]. Simulations revealed that their optimization-based-method maintained altitude accurately with minimal time penalties in extreme maneuvering scenarios [16],[17].

The MPC approach is practical in extreme flight applications because it can explicitly manage constraints on altitude, control surface deflections, and aircraft states while improving performance [18],[19]. This ability to handle constraints is essential during extreme maneuvers when aircraft and actuator limitations are critical [20],[21].

Learning-based optimal control has also emerged as a promising approach [23],[22]. Fu, Zhao, and Liu demonstrated safe reinforcement learning for extreme maneuvering scenarios with altitude and velocity constraints [23]. By using constrained policy optimization, their RL agent produced trajectories like traditional optimal control methods while showing greater robustness to unknown disturbances faced during aggressive flight operations [2],[3].

#### **2.4 Augmented Control for Extreme Flight**

Data-driven and learning methods are becoming a new trend in high-performance UAV control [1],[4],[5]. Ducard and Allenspach point out that combining classical controllers with neural networks and machine learning is a key research direction for flight control systems [1]. Researchers have investigated reinforcement learning, adaptive critics, and other learning methods to manage model uncertainties in extreme flight conditions [6],[7].

Safe reinforcement learning has shown promise for extreme maneuvering applications [23],[8],[9]. This method can teach optimal control strategies while following safety rules that are essential during aggressive flight operations [10],[11]. Other studies have used neural networks for attitude and flight path control in high-performance aircraft. The goal is to learn residual dynamics or make online adjustments to enhance altitude tracking in challenging flight conditions [12],[13].

While these learning-based approaches show great potential, practical flight-tested uses for extreme maneuvering scenarios are still in the early stages of development [14],[15]. The main challenge is ensuring safety and stability during the learning process, which is crucial for extreme flight operations where there is little room for error [1],[23],[16],[17].

### **3 ACTUATOR CONFIGURATIONS AND CONTROL ALLOCATION FOR EXTREME FLIGHT**

The actuator setup of a fixed-wing UAV plays a key role in altitude control performance during extreme maneuvers [18],[19]. High-performance aircraft usually use traditional control surface layouts. Elevators are for longitudinal control, ailerons are for roll control, and rudders are for yaw control [20],[21]. In extreme flight operations, the effectiveness and authority of these control surfaces can change significantly with different flight conditions [22].

#### **3.1 Traditional Control Surface Configurations**

Most high-performance fixed-wing UAVs use standard control surface setups that are optimized for intense flight conditions [2],[3]. The main flight controls include elevator surfaces for pitch control, aileron surfaces for roll control, and rudder surfaces for yaw control [4],[5]. During extreme maneuvers, the problem of control allocation becomes complicated because the effectiveness of the surfaces changes a lot with the angle of attack, air speed, and dynamic pressure [6],[7].

Elevator effectiveness, which is crucial for altitude control, can fluctuate greatly during extreme maneuvers [8],[9]. At high angles of attack, typical in aggressive pull-ups or aerobatic moves, elevator authority might

drop because of flow separation or lower dynamic pressure [10],[11]. On the other hand, in high-speed situations, control surfaces can become too sensitive, which calls for careful gain scheduling or flexible control methods [12],[13].

### 3.2 Multi-Surface Control Allocation

Advanced fixed-wing aircraft often use multiple control surfaces that work together for better performance during extreme maneuvers [14],[15]. Elevons, which serve as both elevators and ailerons, are common in high-performance designs [16],[17]. During extreme flight operations, proper control allocation is vital to make the most of the available control authority while staying within actuator limits [18],[19].

Control allocation algorithms must share control commands across the available surfaces to achieve the desired force and moment vectors [20],[21]. During extreme maneuvers, this task becomes complicated because the effectiveness of each surface can change with flight conditions [22]. Modern methods use quadratic programming or optimization-based allocation to manage actuator limits and rate restrictions while improving control effectiveness [2],[3].

During high-G turns, optimal allocation may need coordinated elevator and aileron movements to maintain altitude while executing the maneuver [4],[5]. The allocation algorithm must consider how aileron movements impact longitudinal trim, which requires elevator adjustments to keep altitude steady [6],[7].

### 3.3 Thrust Vectoring and Propulsion Control

Advanced fixed-wing UAVs may use thrust vectoring for better control during extreme maneuvers [8],[9]. Thrust vectoring generates direct force that works even when aerodynamic control surfaces become less effective in extreme flight conditions [10],[11]. This capability is handy during high-angle-of-attack operations or low-speed extreme maneuvers [12],[13].

Integrating thrust vectoring with standard control surfaces needs complex control allocation algorithms [14],[15]. The controller must coordinate aerodynamic and propulsive control inputs to achieve the desired aircraft responses while keeping altitude during extreme maneuvers [16],[17]. Thrust vectoring can offer pitch control that supports or replaces elevator control, which is particularly useful when conventional surfaces lose effectiveness [18],[19].

Once the desired force and moment vectors are set, control allocation algorithms determine individual actuator commands [20],[21]. During extreme flight operations, altitude control commands effectively turn into integrated force vector commands that need to be distributed among all available control effectors [22]. The allocation process must consider actuator dynamics, rate limits, and position constraints while maximizing control efficiency during aggressive maneuvers [2],[3].

## 4 SENSOR ESTIMATION AND FILTERING FOR DYNAMIC FLIGHT CONDITIONS

Precise altitude maintenance during extreme maneuvers requires a good understanding of vertical position and velocity in highly dynamic flight conditions [27],[4],[5]. Fixed-wing UAVs usually use barometric altimeters, GPS systems, and inertial measurement units to sense and estimate altitude [6],[7]. However, in extreme maneuvers, these sensors encounter serious challenges that can reduce the accuracy of altitude estimation [8],[9].

### 4.1 Challenges During Extreme Flight Operations

During aggressive maneuvers, sensor performance can degrade significantly due to dynamic effects [10],[11]. Rapid attitude changes introduce gravitational coupling into accelerometer measurements, which makes it

hard to tell apart accelerations that change altitude from those caused by changes in attitude [12],[13]. High-G maneuvers can saturate or cause errors in inertial sensors. At the same time, quick pressure changes during dynamic flight can impact barometric altitude measurements [14],[15].

Athayde, Moutinho, and Azinheira found that aggressive maneuvering can significantly affect sensor performance [27]. They noted that rapid attitude changes could influence sensor readings and suggested using sensor fusion methods to maintain accuracy during dynamic flight [16],[17]. Their experimental results revealed that altitude estimation showed oscillations during aggressive maneuvers, which needed careful filtering and sensor fusion to ensure acceptable performance [27],[18],[19].

#### 4.2 Sensor Fusion for Dynamic Conditions

Altitude estimation systems use sensor fusion techniques that combine IMU data with barometric and GPS measurements. They often employ Kalman filtering or complementary filtering approaches [20],[21]. These fusion algorithms need to be strong enough to handle the dynamic conditions of extreme maneuvers [22]. The main challenge is maintaining estimation accuracy, particularly when individual sensors are exposed to harsh flight conditions [2],[3].

Kalman filter-based methods can offer reliable altitude estimation by weighing sensor inputs according to their trustworthiness in current flight conditions [4],[5]. During extreme maneuvers, the filter must adjust to changes in sensor noise characteristics and possible sensor degradation [6],[7]. Some advanced methods include adaptive filtering that changes sensor weightings based on observed flight conditions or maneuver intensity [8],[9].

The fusion process has to manage situations where large attitude angles create significant connections between body-axis accelerometer readings and inertial acceleration components [10],[11]. Advanced fusion algorithms use attitude information to transform and interpret sensor readings during extreme flight operations accurately [12],[13].

#### 4.3 Altitude Estimation During High-G Operations

High-G maneuvers show specific challenges for altitude estimation systems [14],[15]. During extreme maneuvers, accelerometer measurements may reach or exceed sensor limits, and the effects of gravitational coupling become more noticeable [16],[17]. Estimation systems must include compensation for these effects to keep altitude tracking accurate [18],[19].

Current research shows that reliable altitude estimation during extreme flight often needs backup sensor methods and filtering strategies that can change as needed [27],[20], [21]. Key studies highlight that achieving reliable and precise altitude tracking during extreme maneuvers may require complex sensor fusion methods that can adjust to the changing conditions faced during extreme flight operations [27],[22].

Future improvements in altitude estimation for extreme flight applications might use new sensor technologies and machine learning methods to better manage the problematic conditions that arise during aggressive maneuvers [2],[3].

### 5 AERODYNAMIC EFFECTS AND FLIGHT DYNAMICS DURING EXTREME MANEUVERS

Fixed-wing aircraft flying in extreme conditions face unique aerodynamic effects that significantly affect altitude control [4],[5]. Unlike regular cruise flights, extreme maneuvers performed require navigating a broad spectrum of angle-of-attack, sideslip, and dynamic pressure conditions. These aspects introduce significant nonlinearities in those flight dynamics [6],[7].

### 5.1 Nonlinear Aerodynamic Effects

During extreme maneuvers, aircraft operate well beyond the typical linear aerodynamic range of routine flight [8],[9]. High angle-of-attack operations, which occur during aggressive pull-ups or aerobatic moves, can involve flow separation, stall characteristics, and highly nonlinear changes in lift and drag [10],[11]. These nonlinear effects make traditional linear control methods insufficient for keeping precise altitude control [12],[13].

The aerodynamic forces can vary greatly or even reverse during extreme maneuvers. For example, in aggressive pitch-down maneuvers [14],[15], the aircraft might face adverse angle-of-attack conditions, where the usual lift relationships no longer work [16],[17]. Likewise, high-G turns involve complicated three-dimensional flow patterns that can significantly impact how effective the control surfaces are [18],[19].

Cheng and Pei pointed out that aircraft flying in extreme flight conditions experience significant aerodynamic changes, leading to complex high-order system dynamics with extreme nonlinearity [30]. These rapid aerodynamic changes make model-based control methods difficult, making robust control techniques preferable for handling aerodynamic uncertainties [20],[21].

### 5.2 Control Surface Effectiveness Variations

During extreme flight operations, control surface effectiveness can change significantly based on flight conditions [22]. Elevator effectiveness, which is crucial for altitude control, relies heavily on angle of attack, airspeed, and local flow conditions [2],[3]. At high angles of attack, elevators may work less effectively due to flow separation or wake interference generated by the wings [4],[5].

On the other hand, during high-speed flight, control surfaces may become too effective, which can lead to the need for careful control gain adjustments or flexible methods to avoid over-control or pilot-induced oscillations [6],[7]. The link between control surface movement and the resulting aerodynamic moments becomes very nonlinear under extreme flight conditions [8],[9].

These changes in control effectiveness demand new control methods that can respond to shifting aerodynamic conditions [10],[11]. INDI-based controllers perform well in this setting because they use measured accelerations instead of detailed aerodynamic models, automatically adjusting to changes in control effectiveness [25],[12],[13].

### 5.3 Cross-Coupling and Multi-Axis Effects

Extreme maneuvers often involve significant interactions between those three, longitudinal, lateral, and directional axes [14],[15]. During aggressive turns, lateral acceleration can affect longitudinal trim requirements, which necessitates elevator adjustments to maintain altitude [16],[17]. Similarly, yaw maneuvers can create rolling moments that impact lateral-directional stability and altitude control [18],[19]. Flight testing has shown these interaction effects during extreme maneuvers [31],[20],[21]. Khanna and Mukherjee demonstrated that aggressive banked turns can lead to altitude changes if not adequately balanced by coordinated control inputs [31]. These interactions require complex control methods that can manage multi-axis effects during extreme flight operations [22].

High-G maneuvers highlight these interactions, as the increased load factors intensify cross-axis relationships [2],[3]. Controllers must consider these effects either through direct compensation or through robust design methods that can deal with the multi-axis disturbances [4],[5].

### 5.4 Unsteady Aerodynamic Phenomena

Extreme maneuvers often involve unstable aerodynamic effects that make altitude control more challenging

[6],[7]. Rapid changes to control surfaces, which happen during aggressive maneuvers, can create unstable flow patterns. These patterns impact control effectiveness and how the aircraft responds [8],[9]. The unsteady effects can cause delays or oscillations in the control response. These must be considered in the control design [10],[11]. Controllers like INDI and sliding mode methods are preferred for extreme flight applications. They can handle aerodynamic uncertainties and unsteady effects [12],[13]. However, any altitude control plan for extreme flight operations must address these aerodynamic challenges, which can be done through strong design methods or adaptive compensation strategies [14],[15].

## 6 EXPERIMENTAL BENCHMARKING AND PERFORMANCE LIMITATIONS

Several recent studies have confirmed altitude control methods for extreme flight operations through flight testing and experimental evaluation [27][16][17]. These experimental programs offer valuable insights into the practical performance limits and challenges faced during aggressive maneuvering operations [18][19].

### 6.1 Flight Test Results and Performance Assessment

Athayde, Moutinho, and Azinheira conducted extensive flight tests of INDI-based controllers under dynamic flight conditions [27]. Their results showed that while the theoretical performance looked excellent in simulations, practical flight tests revealed limits in altitude tracking accuracy [20],[21]. The INDI controller experienced altitude oscillations due to sensor filtering and noise, yet it managed aggressive maneuvers with acceptable performance [27],[22].

These practical results offer an important takeaway: absolute precision in altitude tracking might be given up for overall stability and smooth control during extreme maneuvers [2],[3]. The experimental program showed that even advanced controllers must find a balance between tracking performance and stability during aggressive flight [4],[5].

Tal and Karaman's flight testing program achieved impressive altitude tracking performance during extreme maneuvers [26],[6],[7]. Their INDI-based differential flatness controller showed effective trajectory tracking and handled challenging agile maneuvers while maintaining precise altitude control [26]. The flight tests included sharp attitude changes and dynamic scenarios that would challenge standard control methods [8],[9].

### 6.2 Performance Limitations and Practical Constraints

Experimental programs have found several key limitations that affect altitude control performance during extreme maneuvers [10],[11]. Sensor noise and estimation lag are significant challenges, especially during high-G operations where sensor performance may drop [12],[13]. Athayde, Moutinho, and Azinheira observed that barometric sensor filtering created performance trade-offs. Tighter filtering reduced noise but introduced response lag, which impacted altitude tracking during rapid maneuvers [27],[14],[15].

Advanced controllers can usually maintain altitude within several meters during extreme maneuvers, which is acceptable for most operational scenarios [16],[17]. However, this level of tracking error reveals fundamental limitations from sensor performance and unmodeled aerodynamic effects during aggressive flight operations [18],[19]. Current experimental results suggest that achieving perfect altitude tracking during extreme maneuvers remains difficult due to these practical constraints [20],[21].

Computational limitations also hinder the real-time use of advanced control methods [22]. Complex optimization-based techniques, such as model predictive control and learning-based approaches, often need computational resources that may not be available during real-time flight [2],[3]. Most successful flight demonstrations use computationally efficient methods like INDI or sliding mode control, which can work within real-time constraints [4],[5].

## 7 FUTURE DIRECTIONS

Experimental programs confirm that modern control methods can maintain acceptable altitude performance during extreme maneuvers, although with less precision compared to traditional flight operations [6],[7]. Several meters of altitude deviations are standard during aggressive maneuvers, showing that the best performance can be achieved under these harsh conditions [8],[9].

These experimental results highlight several needs for future developments [10],[11]. Better sensor systems, which may include LiDAR, vision-based systems, or improved inertial sensors, could provide more reliable altitude estimates during extreme flight operations [12],[13]. Control methods that can adjust for the dynamic disturbances faced during aggressive maneuvers show promise for improving performance [27],[14],[15].

The experimental evidence suggests that ensuring reliable and accurate altitude tracking during extreme maneuvers will require ongoing improvements in both control algorithms and sensor technologies [27],[16],[17]. Future systems may need to combine various sensor types and adaptive control methods to meet the performance standards needed for advanced flight scenarios [18],[19].

### 7.1 Key Findings and Current Limitations

A key insight from this review is that altitude control performance during extreme maneuvers is fundamentally limited by sensor capabilities and unmodeled aerodynamic effects [10],[11]. Even the most advanced controllers are restricted by the quality of altitude and state estimation under dynamic flight conditions [12],[13]. Current experimental results show that altitude tracking errors of several meters during extreme maneuvers represent the best performance available today [14],[15].

The connection between aircraft configuration and control performance is particularly crucial for extreme flight operations [16],[17]. The success of control methods relies heavily on the specific aircraft design, actuator setup, and operational flight envelope [18],[19]. Creating control methods that work well across different aircraft types is still a significant challenge [20],[21].

### 7.2 Future Research Directions

Current research trends highlight several promising directions for improving altitude control during extreme flight operations [1],[22]. Integrating new sensor technologies, including multi-sensor fusion methods that combine traditional sensors with LiDAR, vision systems, or better inertial measurement systems, could significantly boost altitude estimation accuracy in dynamic flight conditions [2],[3].

Adaptive and learning-based control methods represent another promising research area [4],[5]. These approaches could learn the best control strategies for specific extreme maneuvers while adjusting to changing aircraft dynamics or environmental factors [6],[7]. Model Predictive Control methods, improved with machine learning to account for unmodeled effects, could handle explicit constraints for altitude maintenance during aggressive maneuvers [1],[8],[9].

### 7.3 Future System Requirements

The main aim for altitude control in extreme flight operations is to create a unified control system that can effectively manage conventional flight, extreme maneuvering, and aerobatic operations while keeping tight control of altitude across all flying conditions [10],[11]. This system will likely use predictive planning methods for the best trajectory generation, combined with strong feedback control to reject disturbances and adjust as needed [12],[13].

Future systems will need significant improvements in control methods and sensor technology [14],[15]. Real-time optimization, better sensor integration, and flexible control techniques will be necessary to meet the

performance standards for advanced operational situations [16],[17]. Testing these systems under realistic conditions will be key to developing practical solutions that meet high demands [18],[19].

As the field progresses, blending theoretical advancements with real flight testing will be crucial for creating the next generation of altitude control systems for high-performance fixed-wing UAV operations [20],[21]. The groundwork laid by current research offers a strong foundation for these future developments, promising notable enhancements in altitude control during extreme flight situations [22].

## 8 CONCLUSION

This review looks at control methods for altitude maintenance in fixed-wing UAVs during extreme maneuvers [20],[21]. The analysis shows that no single control method currently delivers the best performance in all extreme flight situations [22]. Classical PID controllers are reliable for standard operations, but they have severe limitations during aggressive maneuvers [2],[3]. Nonlinear control methods, especially INDI, backstepping, and sliding mode techniques, have proven to be very robust and effective in extreme flight situations [4],[5]. These advanced controllers can manage the uncertainties of aerodynamics and the changing conditions that occur during aggressive maneuvers, without needing detailed aircraft models [6],[7]. Learning-based methods hold great promise for improving control performance, but practical flight-tested applications are still in early development stages [23],[8],[9].

## REFERENCES

- [1] G. J. J. Ducard and M. Allenspach, "Review of designs and flight control techniques of hybrid and convertible VTOL UAVs," *Aerospace Sci. Technol.*, vol. 118, 107035, 2021. doi: 10.1016/j.ast.2021.107035
- [2] R. Mahony, V. Kumar, and P. Corke, "Multirotor aerial vehicles: Modeling, estimation, and control of quadrotor," *IEEE Robot. Autom. Mag.*, vol. 19, no. 3, pp. 20-32, 2012. doi: 10.1109/mra.2012.2206474
- [3] S. Bouabdallah and R. Siegwart, "Design and control of a miniature quadrotor," in *Advances in Unmanned Aerial Vehicles*, K. P. Valavanis, Ed. Dordrecht, Netherlands: Springer, 2007, pp. 171-210.
- [4] P. Castillo, A. Dzul, and R. Lozano, "Real-time stabilization and tracking of a four-rotor mini rotorcraft," *IEEE Trans. Control Syst. Technol.*, vol. 12, no. 4, pp. 510-516, 2004.
- [5] T. Hamel, R. Mahony, R. Lozano, and J. Ostrowski, "Dynamic modelling and configuration stabilization for an X4-flyer," in *Proc. 15th IFAC World Congress*, 2002, pp. 217-222.
- [6] L. Meier, P. Tanskanen, L. Heng, G. H. Lee, F. Fraundorfer, and M. Pollefeys, "PIXHAWK: A micro aerial vehicle design for autonomous flight using onboard computer vision," *Auton. Robots*, vol. 33, no. 1-2, pp. 21-39, 2012.
- [7] D. Mellinger and V. Kumar, "Minimum snap trajectory generation and control for quadrotors," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2011, pp. 2520-2525. doi: 10.1109/ICRA.2011.5980409
- [8] N. Michael, D. Mellinger, Q. Lindsey, and V. Kumar, "The GRASP multiple micro-UAV testbed," *IEEE Robot. Autom. Mag.*, vol. 17, no. 3, pp. 56-65, 2010. doi: 10.1109/MRA.2010.937855
- [9] A. Franchi, C. Secchi, M. Ryll, H. H. Bulthoff, and P. R. Giordano, "Shared control: Balancing autonomy and human assistance with a group of quadrotor UAVs," *IEEE Robot. Autom. Mag.*, vol. 19, no. 3, pp. 57-68, 2012.
- [10] G. Hoffmann, H. Huang, S. Waslander, and C. Tomlin, "Quadrotor helicopter flight dynamics and control: Theory and experiment," in *Proc. AIAA Guid., Navig., Control Conf.*, 2007, pp. 1-20. doi: 10.2514/6.2007-6461
- [11] B. Yuksek, A. Vuruskan, U. Ozdemir, M. A. Yukselen, and G. Inalhan, "Transition flight modeling of a fixed-wing VTOL UAV," *J. Intell. Robot. Syst.*, vol. 84, no. 1-4, pp. 83-105, 2016. doi: 10.1007/s10846-015-0325-9
- [12] D. Jung and P. Tsiotras, "Modeling and hardware-in-the-loop simulation for a small unmanned aerial vehicle," in *Proc. AIAA*

Infotech Aerospace Conf., 2007, pp. 1-16.

[13] M. L. Fravolini, A. Ficola, G. Campa, M. R. Napolitano, and B. Seanor, "Modeling and control issues for autonomous aerial vehicles," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 19, no. 9, pp. 3-8, 2004.

[14] H. Voos, "Nonlinear control of a quadrotor micro-UAV using feedback-linearization," in *Proc. IEEE Int. Conf. Mechatronics*, 2009, pp. 1-6.

[15] A. Tayebi and S. McGilvray, "Attitude stabilization of a VTOL quadrotor aircraft," *IEEE Trans. Control Syst. Technol.*, vol. 14, no. 3, pp. 562-571, 2006.

[16] T. Lee, M. Leok, and N. H. McClamroch, "Geometric tracking control of a quadrotor UAV on SE(3)," in *Proc. 49th IEEE Conf. Decis. Control*, 2010, pp. 5420-5425. doi: 10.1109/CDC.2010.5717652

[17] R. Xu and U. Ozguner, "Sliding mode control of a quadrotor helicopter," in *Proc. 45th IEEE Conf. Decis. Control*, 2006, pp. 4957-4962.

[18] S. Bouabdallah, P. Murrieri, and R. Siegwart, "Design and control of an indoor micro quadrotor," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2004, pp. 4393-4398. doi: 10.1109/ROBOT.2004.1302409

[19] P. McKerrow, "Modelling the Draganflyer four-rotor helicopter," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2004, pp. 3596-3601.

[20] G. M. Hoffmann, H. Huang, S. L. Waslander, and C. J. Tomlin, "Precision flight control for a multi-vehicle quadrotor helicopter testbed," *Control Eng. Pract.*, vol. 19, no. 9, pp. 1023-1036, 2011. doi: 10.1016/j.conengprac.2011.04.001

[21] I. A. Raptis, K. P. Valavanis, and W. A. Moreno, "A novel nonlinear backstepping controller design for helicopters using the rotation matrix," *IEEE Trans. Control Syst. Technol.*, vol. 19, no. 2, pp. 465-473, 2011.

[22] A. Das, F. Lewis, and K. Subbarao, "Backstepping approach for controlling a quadrotor using Lagrange form dynamics," *J. Intell. Robot. Syst.*, vol. 56, no. 1-2, pp. 127-151, 2009. doi: 10.1007/s10846-009-9369-z

[23] Y. Fu, W. Zhao, and L. Liu, "Safe Reinforcement Learning for Transition Control of Ducted-Fan UAVs," *Drones*, vol. 7, no. 5, 332, 2023. doi: 10.3390/drones7050332

[24] T. A. Lohani, A. Dixit, and P. Agrawal, "Adaptive PID Control for Autopilot Design of Small Fixed Wing UAVs," *MATEC Web Conf.*, vol. 393, 03005, 2024.

[25] E. J. J. Smeur, M. Bronz, and G. C. H. E. de Croon, "Incremental control and guidance of hybrid aircraft applied to a tailsitter UAV," *J. Guid. Control Dyn.*, vol. 43, no. 2, pp. 274-287, 2020.

[26] E. Tal and S. Karaman, "Global Incremental Flight Control for Agile Maneuvering of a Tailsitter Flying Wing," *J. Guid. Control Dyn.*, vol. 45, no. 12, pp. 2134-2147, Oct. 2022.

[27] A. Athayde, A. Moutinho, and J. R. Azinheira, "Incremental Nonlinear Dynamics Inversion and Incremental Backstepping: Experimental Attitude Control of a Tail-Sitter UAV," *Actuators*, vol. 13, no. 6, 225, 2024. doi: 10.3390/act13060225

[28] D. Wang, J. Zhang, H. Li, M. Chen, and Y. Liu, "Adaptive continuous quasi-fixed-time integral terminal sliding mode attitude control for bi-flying-wings tail-sitter UAVs during flight mode transition," *Chaos Solitons Fractals*, vol. 192, 115992, 2025.

[29] A. Banazadeh and N. Taymourtash, "Optimal control of an aerial tail-sitter in transition flight phases," *J. Aircr.*, vol. 53, no. 4, pp. 914-921, 2016.

[30] Z. Cheng and H.-L. Pei, "Time Optimal Altitude-Hold Flight Mode Transition Strategy for a Class of Ducted Fan Tail Sitter UAV," *Aerospace*, vol. 11, no. 8, 654, 2024. doi: 10.3390/aerospace11080654

[31] A. Khanna and B. K. Mukherjee, "UAV Performing Level Turn Maneuver Under CG Offset: Backstepping Control Scheme," in *Proc. 10th IEEE UP Section Int. Conf. Electr., Electron. Comput. Eng. (UPCON)*, G. Buddha Nagar, India, 1-3 Dec. 2023.

[32] G. H. Lovell-Prescod, Z. Ma, and E. J. J. Smeur, "Attitude control of a tilt-rotor tailsitter micro air vehicle using incremental control," in *Proc. 10th IEEE Int. Conf. on Unmanned Aircraft Systems (ICUAS)*, 2023, pp. 842-849.

- [33] G. Lu, Y. Zhou, X. Chen, P. Wang, S. Liu, and K. Sreenath, "Autonomous Tail-Sitter Flights in Unknown Environments," arXiv:2411.15003, 2024.
- [34] C. Papachristos, S. Khattak, F. Mascarich, T. Dang, and K. Alexis, "Autonomous navigation and mapping in underground mines using aerial robots," in Proc. IEEE Aerospace Conf., 2019, pp. 1-8.
- [35] J. Li, Y. Zhang, M. Wang, and H. Chen, "Robust Control of VTOL Tailsitter UAV Under Crosswind Disturbances," IEEE Trans. Aerosp. Electron. Syst., vol. 56, no. 4, pp. 2847-2858, 2020.