

Which stability-enhancement methods appear most effective for quadrotor UAVs?

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Abstract. The use of quadrotor Unmanned Aerial Vehicles (UAVs) in a wide variety of tasks, ranging from environmental monitoring to agriculture spraying of crops and disaster zone rescues, benefits from the small size, ability to perform vertical takeoff and landing and better maneuverability. However, the lightness of their structure and high level of nonlinearity make quadrotors very vulnerable to the influence of different kinds of disturbances such as wind gusts, sensor errors, thermal drift and actuator biases. Hence, one of the most important research areas related to quadrotors is concerned with their stability and attracts a lot of scientific interest due to both practical importance and possibilities to contribute to the state-of-the-art. This research focuses on various control system approaches that have been proposed in order to improve the stability of quadrotors, including classic Proportional–Integral–Derivative (PID), Linear Quadratic Regulator (LQR), and modern approaches like Sliding Mode Control (SMC), backstepping, fuzzy logic and neural networks control. The comparative analysis touches upon the issues of nonlinearity handling, performance in the presence of disturbances, and timely computation. In particular, the results obtained during this research suggest that modern control strategies show better performance when working in a noisy environment, while classical approaches still have some value in terms of their simplicity, less requirements in computing power and other implementation aspects. As to the final conclusion, there is no universal best method of controlling a quadrotor. At the same time, the research shows that modern approaches offer better options in case of performing difficult tasks, while classics are good enough for low-level tasks.

Keywords: quadrotor UAV, stability enhancement, control methods, PID control

1. Introduction

Quadrotor UAVs display operational efficiency that is dependent on flight control. With the lightweight nature of these UAVs and the fact that they experience strong coupling and underactuation, quadrotor UAVs are vulnerable to disturbances like gusts of wind and uncertainties [1]. Robust control methods that can be used to reduce these problems and enhance flight stability have been a major focus in the study of quadrotor UAVs.

Several methods have been suggested for overcoming the problem of quadrotor instability during research and development. Standard control methods like PID controllers have proven to be effective in UAV flight systems because of their simple nature [2]. Nonlinear advanced control systems like SMC and those involving neural networks have been considered to solve the problems of disturbances and coupling [3]. However,

despite the stability advantages of these systems, they face practical challenges like chatter effects and excessive computing power requirements. The next section highlights some advanced control methods used in UAV flight systems in comparison with other approaches.

This research aims to identify the most effective control-based stability enhancing methods for UAVs based on available scientific knowledge. This will be achieved via comparative analysis of the literature available and evaluating each method by three key criteria. Although UAV stability depends on various factors like the type of airframe and its components, as well as coordination among multiple UAVs, the focus of this research is the problem of controlling stability in a single quadrotor vehicle. Therefore, the methods will be compared according to their robustness and ability to work with nonlinear dynamic systems, as well as practical implementation cost.

Finally, it should be noted that in contrast with the discussed stability enhancement via controls, there are also other ways to improve UAV stability, for instance, by improving the airframe design or applying formation rigid control.

2. Research review

This section reviews the key literature on quadrotor UAV stability, covering definitions, system components, and the main control methods used for stability enhancement.

2.1. Definition of quadrotor UAVs

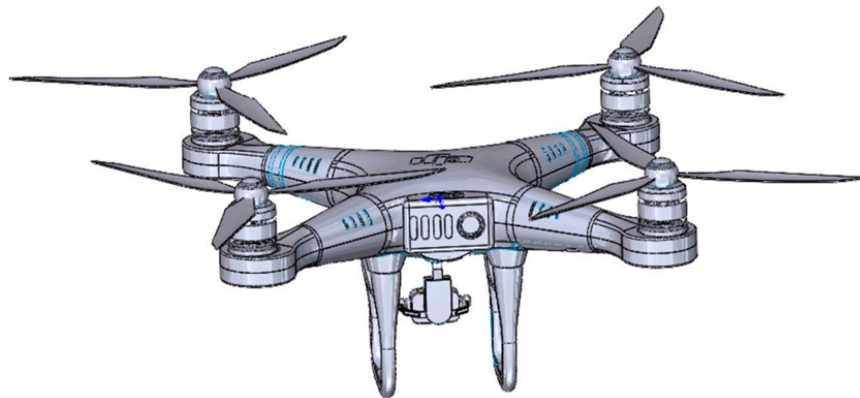


Figure 1. Quadrotor frame [4]

The quadrotor, also known as a quadcopter, is a multirotor aircraft capable of generating lift and maneuverability using its four rotors. Two rotors turn clockwise, while two others turn counterclockwise to maintain torque balance. As outlined in foundational texts on multicopter design [5], a quadrotor is an example of an underactuated system having four inputs yet six degrees of freedom, thus making the system highly nonlinear and coupling dynamics tightly [6], as shown in Figure 1.

Apart from the conventional four-rotor airframe design, there exist other unconventional airframe configurations that can be applied to achieve some particular advantages of UAVs. As an example, while the H-configuration airframes may provide more structural benefits for some purposes, alterations in the center of mass in changing configuration settings can make maintaining attitude and continuing operation complicated [7]. This serves as the proof that stability may depend not only on the control algorithm but also on the specific design of the UAV platform.

Table 1. Comparison of drone configurations [8]

Feature	X- Configuration	+ Configuration	H-Configuration	Y-Configuration
Stability	High	Moderate	High	Moderate
Agility	High	Moderate	Moderate	Low
Camera Obstruction	None	Moderate	None	Moderate
Aerodynamics	Efficient	Less efficient	Moderate	Efficient
Weight Distribution	Balanced	Less efficient	Good	Less efficient
Payload Handling	Excellent	Good	Moderate	Limited

It can be seen from Table 1 that the X-configuration strikes an excellent balance between stability, agility, and carrying payload [8]. Its symmetric structure results in optimal thrust distribution and reduction of unwanted vibrations, making it suitable for high-precision applications, such as imaging and surveillance. While airframe configuration is not a control method itself, it defines the stability of the configuration that must be regulated by the control method used. The need to consider this factor when choosing a control method lies in the fact that a stable configuration reduces the load on the control method that must stabilize the UAV.

The communication module ensures that the information transfer between the UAV and the ground station is wireless. It consists of the transmitters, receivers, and corresponding communication protocols needed for transferring data. In general, the transmitter is located in the ground control station to send commands, and the receiver is positioned on board the UAV to receive them. While flight stability is ensured by the control system, stable communication is required for safe control. Thus, all of these elements provide the basis for the application of a method for stabilizing the UAV, the effectiveness of which will depend on the stability of all these modules.

Navigation means determining the location, velocity, and orientation of the UAV. This function is considered one of the fundamental requirements for autonomous flight. In actuality, this system combines the data from various sensors to determine the UAV's current position and thus provide the information necessary for guiding and controlling. Besides, the battery acts as the main energy source for the control system on board the UAV.

Power supply provides electrical energy to the UAV's onboard electronics, sensors, controllers, and actuators, serving as its main energy source. Energy efficiency enhancement and increase of battery autonomy are also among the important scientific problems, as the battery life is limited, thus defining the maximum time of autonomous flight.

The controller plays the main part in making decisions for flight control systems. It compares the ideal state with the state obtained through the feedback signal, calculates the control value according to a particular control law, and sends signals to the actuators to guide the UAV into a desirable state. According to the aforementioned process, the controller will be considered one of the key factors of error minimization in terms of both stabilizing and tracking functions. Traditionally, there was a common use of relatively simple linear control approaches because of their relatively low demand in computations. However, with further advancements in modeling and computing power, it is now possible to implement considerably more sophisticated non-linear control approaches in real time [6].

Analysis of scholarly literature shows that there is a notable dichotomy between the two stances on UAV stabilization: the pragmatic approach focused on computational simplicity and a performance-driven approach aimed at robustness against non-linear dynamics. The scholars that can be included in the first group, Chacko,

Neeraj, and Abraham [9] and Sereyvatha et al. [8] argue that linear controllers like PID and LQR cannot be underestimated for their ease of usage and minimal requirement for hardware, making them ideal solutions for cost-effective applications. On the other hand, scholars who investigate complex flight envelope, for instance, Abdulkareem et al. [6] and Wu et al. [4] criticize these approaches by referring to their inefficiency against highly-coupled and underactuated non-linear dynamics. Therefore, they emphasize the advantages of more modern approaches including SMC and NN-based approaches [3]. These control approaches provide a much better disturbance rejection.

Comparing the approaches above, one can conclude that evaluation of control methods cannot be performed simply by comparison between linear and nonlinear approaches. Modern literature suggests that an important factor to consider is their integrability into the whole system. In other words, in order to avoid imposing unnecessary restrictions, nowadays scholars prefer hybrid methods in which theoretical advantages of complicated algorithms are combined with simplicity of execution of classic ones. With regard to the reliability of the information sources, it is best to use peer-reviewed journal articles and review papers. The latter give more thorough comparative analysis based on the former. Peer-reviewed conference papers and case studies may be useful only for a certain problem analysis. Overall, based on the analysis of the quadrotor's physical and operational features, the main goal remains stabilizing its flight.

2.2. Stability enhancement of UAVs

2.2.1. *Concept of stability in quadrotor UAVs*

Stability in quadrotor UAVs implies the ability of the UAV to maintain and recover its predetermined attitude and positioning in the face of either internal or external disturbance forces [10]. Essentially, a stable quadrotor will demonstrate resistance to unwanted perturbations and recover controlled operation through the combined effort of its dynamics model and controller. Due to the inherently strongly coupled and nonlinear behavior of the quadrotor, stability will have to be considered in both its rotation and translational aspects.

In practice, the stability of the quadrotor UAV is subject to a number of environmental and operational variables. An example is the case of the ground effect, which emerges when a rotary-wing UAV operates close to the ground. As a result of this phenomenon, the blade flowfield changes, leading to corresponding changes in aerodynamic forces and moments, which, in turn, will affect flight stability. The intricate relationship between such advanced UAV aerodynamics and flight stability necessitates robust control theories [11]. To overcome these issues and ensure adequate control throughout the entire range of flight altitudes, disturbance compensation or dynamic inversion techniques are used [12]. Consequently, the environment in which the vehicle operates may significantly change requirements for the control system, thus constituting an important aspect of considering different approaches to improving stability.

In terms of control theory, stability analysis of quadrotor Unmanned Aerial Vehicles (UAVs) can be conducted using Lyapunov theory. Lyapunov functions are scalar quantities used to determine whether the system is bounded and converges to an equilibrium point in a controlled manner [13]; however, it should be noted that this specific source is a recent preprint, and the findings of this paper should be viewed skeptically until peer-reviewed by other scientists). If the system state stays within proximity to equilibrium after a disruption, then the system is considered stable, while if the state asymptotically reaches the equilibrium point, then it is described as asymptotically stable. In other words, this approach enables researchers to use mathematics to verify whether a control approach would make a UAV stable instead of relying exclusively on experimental validation. Input-to-state stability is highly relevant for UAVs experiencing external effects since it determines whether the system can retain good behavior despite noisy conditions, uncertainties in the model, and other disturbances.

2.2.2. Reasons why stability enhancement is critical

Stability still represents a critical issue since UAVs used here are nonlinear systems with strong coupling between different elements and dynamics. In path-tracking situations, it becomes crucial to control simultaneously the roll, pitch, yaw, and altitude while compensating for various disturbing factors like winds, modeling uncertainties, and changes in aerodynamics. This aspect makes the design of controllers especially complicated when the UAV is supposed to follow aggressive paths. Tracking of an eight-shaped path requires maintaining not only precise positioning but also keeping the appropriate attitude with limited errors at all times during movement [14]. Therefore, stability improvement becomes essential for accurate automatic flight. Stability issues also become more complex if the UAV has to carry something.

Moreover, many missions undertaken by unmanned vehicles imply that there is a certain payload that should be controlled separately. In this case, when attaching the cargo to the UAV using some kind of a cable, oscillations of the payload create additional force moments affecting the UAV itself. The movements of the UAV and load affect each other creating the problem of stabilization of the whole system [15]. Under these conditions, simple approaches working well in hovering situations can be ineffective. It means that new ways of ensuring stability should be developed that will be effective in a much more difficult real situation. To address these complex stability requirements and bridge the gap between theoretical limits and practical flight, researchers have proposed and refined a spectrum of control algorithms.

2.3. Control methods for stability enhancement

2.3.1. Classical control methods (PID controller)

As show in Figure 2, The Proportional-Integral-Derivative (PID) control is one of the most common control methods utilized in classical systems to stabilize quadrotors due to the simplicity of its implementation and reduced computational effort. Moreover, apart from being the most popular approach, PID control also serves as the baseline for measuring the improvement in performance when considering more complex nonlinear algorithms. A PID control algorithm combines the proportional, integral, and derivative control modes to minimize the difference between the desired and actual states. The proportional mode deals with the present error; the integral mode prevents the presence of static error; the derivative mode improves damping by responding to changes in error rates. In quadrotor systems, PID controllers often operate in a cascade fashion, in which an outer loop controls position while an inner loop controls attitude through rotor speeds, as shown in Table 2.

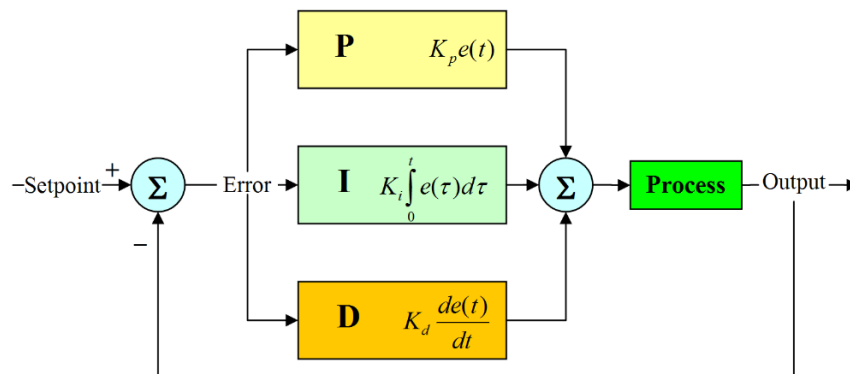


Figure 2. PID control

Table 2. The main advantages of PID control

Adjustment Method ($\uparrow$)	Rise Time	Overshoot	Settling Time	Steady-State Error	Stability
$\uparrow K_p$	Decrease $\downarrow$	Increase $\uparrow$	Small Increase $\uparrow$	Decrease $\downarrow$	Degrade $\downarrow$
$\uparrow K_i$	Small Decrease $\downarrow$	Increase $\uparrow$	Increase $\uparrow$	Significant Decrease $\downarrow$	Degrade $\downarrow$
$\uparrow K_d$	Small Decrease $\downarrow$	Decrease $\downarrow$	Decrease $\downarrow$	Little Change $\rightarrow$	Improve $\uparrow$

The key benefits of PID control include simplicity, tunability, and reliability in typical flight operations. Due to the lack of a complex system model, the integration of PID control into real UAVs becomes relatively easy. Moreover, the relatively low computational effort makes PID control applicable to embedded flight controllers [8]. This statement is highly substantiated by Khalid [10], who provide a thorough peer-reviewed survey on the topic.

On the other hand, there are several limitations associated with PID control. It shows lower efficiency in highly nonlinear systems and may fail under rapidly changing conditions. In the case of external disturbances and uncertainty, tuning of the control gains may be required to maintain acceptable performance. Moreover, PID controllers have weaker disturbance rejection properties compared to other nonlinear and robust control designs [8, 10]. This issue explains further scientific efforts in developing LQR-based methods that seek to formalize tuning in a rigorous mathematical way.

2.3.2. Linear control methods (LQR controller)

Linear Quadratic Regulator (LQR) is a control strategy for linear systems that employs the state feedback control law of $u = -Kx$. Its main goal is to design a feedback gain matrix K , which will minimize the quadratic cost function and thus provide a compromise between the ability of controlling states and required effort of control inputs. Such a trade-off is responsible for popularity of LQR in the design of multivariable control systems, where issues of stabilization and disturbance rejection should be addressed.

In the case of attitude control of quadrotor UAVs, LQR can be applied in order to stabilize such important states as roll, pitch and yaw. Depending on selected Q and R matrices, penalties for each state and control input are assigned, and a designer can tune their values to reach a desirable compromise between quickness of system response and consumption of energy. In this way, LQR is a powerful control method for improvement of performance in quadrotors [9].

Despite its effectiveness, LQR possesses several limitations that have to be taken into account. Firstly, there is no general rule how to choose Q and R , as it is usually determined through trial-and-error procedure and experience of designer. Such procedure can be very time-consuming especially for higher-order systems, possessing many states. Furthermore, LQR is inherently a linear control strategy, which restricts its use in situations when a quadrotor is considerably far from linearized conditions. The requirement of using linearized model is a major drawback of LQR and motivates further investigation of nonlinear control approaches, like Sliding Mode Control (SMC).

2.3.3. Robust control methods (SMC controller)

Sliding Mode Control (SMC) is an effective control methodology based on high-order nonlinear control theory. In essence, the operation of SMC relies on guiding the state of the system to move along a predetermined control surface known as the sliding surface and keeping the state on this surface, which results in significant robustness against disturbances from inside and outside the system (for example, sudden gusts of wind).

Table 3. Comparison of representative sliding mode control approaches for quadrotor UAVs

Control Approach	Computational Cost	Tuning Complexity	Simulation Prevalence	Experimental Implementation
Classical SMC	Low	Medium	High	High
Super-Twisting SMC	Medium	Medium	High	High
Terminal SMC	Medium	Medium	High	Medium
Adaptive SMC	Medium	Medium	High	High
Fractional-Order SMC	High	High	High	Medium
Hybrid/Intelligent SMC	High	High	Medium	Medium

The SMC control strategy belongs to the category of nonlinear robust controls and is heavily used in the quadrotor Unmanned Aerial Vehicle (UAV) applications for its high disturbance rejection ability and robustness under model uncertainties. The main idea of such a control technique lies in moving the state of the system on the sliding surface and maintaining movement along the surface with discontinuous control action. After entering the sliding mode, the controller becomes highly robust to parametric changes and external perturbations, such as gusts of wind.

The computational requirements, tuning difficulty, popularity of the method in simulations and experiments are compared in Table 3. As follows from the table, the classical SMC possesses low computational demands and is very popular since it is rather easy to implement and perform quite well. In turn, the super-twisting SMC represents an improvement since it reduces chattering without losing much of what is good about classical SMC. This is why it is frequently implemented in simulations and experimental researches. It should be mentioned that terminal SMC can converge to the sliding surface in finite time; however, the use of the algorithm seems to be less popular. Adaptive SMC is especially attractive when dealing with UAVs because it allows taking into account uncertainties and time-varying conditions. Meanwhile, fractional-order SMC and intelligent/hybrid versions of SMC require greater computational resources.

Considering the types of Sliding Mode Control (SMC) listed in Table 3, super-twisting SMC and adaptive SMC can be considered most promising in terms of compromise between robustness, implementability and applicability. Classic SMC remains useful because of simplicity, however, the aforementioned problem with chattering may negatively affect practical performance. Advanced SMC may perform better in theory but at the cost of additional computations and other negative effects.

First and foremost, SMC provides an increased level of robustness regarding external disturbances and modeling uncertainties which is especially important for the application of sliding mode control to strongly coupled nonlinear system like quadrotor Unmanned Aerial Vehicles (UAVs). Super-twisting SMC, for example, achieves two orders of sliding where both sliding variable and its derivative tend to zero. As a result, this allows achieving smoother control with robustness still present.

However, there are several problems associated with SMC. Perhaps the best-known disadvantage of SMC is a phenomenon called chattering resulting from discontinuity in switching actions, excitation of unmodeled dynamics and faster rate of actuator wear. Some advanced SMC methods require further complicated parameter settings and increased computational capabilities. The same applies to fractional-order SMC since the presence of the so-called long-memory effect adds extra.

2.3.4. Advanced and intelligent control methods (MPC controller)

Among advanced control techniques, Model Predictive Control (MPC) may be considered one of the most typical approaches for use with quadrotor UAVs. MPC employs a mathematical model to predict the behavior

of the system in the next period and calculates a control action that optimizes the objective function. This approach helps the UAV meet its performance criteria while considering limitations of the system.

One of the key advantages of MPC is that it is able to solve multivariable control problems with multiple constraints imposed on them. In the case of quadrotor UAVs, such properties of the controller are especially valuable since the quadrotor usually needs to fly in conditions when there are constraints imposed on actuators, as well as constraints related to the need for safe flight. The predictive nature of MPC means that the controller is able to take into account future deviations from the desired values.

Nonetheless, MPC possesses several deficiencies. The fact that solving the optimization problem on the go in every control iteration requires much more computational power than other conventional control systems do. Such a requirement might result in decreased responsiveness in situations where the UAV functions in dynamic environments or when there is a restriction in computing capacity onboard the aircraft. Therefore, despite all the benefits offered by MPC, its use becomes more problematic compared to the application of other controls. Altogether, the four controllers form a continuum ranging from the simplest (PID) to the most advanced one (MPC). At the same time, various types of Sliding Mode Control (SMC) fit perfectly between these extremes.

3. Discussion

These three criteria—nonlinear capability, disturbance rejection, and implementation cost—were selected because they represent the dimensions most commonly used to compare control methods in the existing literature, and each relates directly to the real-world demands of quadrotor applications.

3.1. Nonlinear capability

With regard to the nonlinear nature of the quadrotor UAVs' dynamical behavior as mentioned in section 1.2, this section considers the effectiveness of different controllers in handling this situation. In this case, traditional control techniques, including PID and LQR, seem to be rather ineffective under highly nonlinear circumstances. Despite the appeal of simplicity offered by the PID controller, it can be noted that fixed gains chosen based on near-hovering operation conditions may turn out to be inadequate when the flight regime significantly departs from this situation. It is quite possible for the controller to produce undesired effects like overshooting, oscillatory responses, and decreased accuracy of control. At the same time, even though LQR controller ensures state-feedback in a consistent manner, its effectiveness may decrease dramatically once the UAV becomes too far from the linear operation regime, since it works according to a linearized model. In comparison to these techniques, other more advanced and robust techniques prove themselves to be more effective under nonlinear conditions because of their reduced dependence on linearity and ability to manage uncertainties. For example, as highlighted by Abdulkareem et al. [6], SMC demonstrates high effectiveness in nonlinear scenarios because its sliding surface operates independently of a linearized model constraint. Furthermore, Yue and Bacha et al. corroborate that when dealing with strongly coupled dynamics, advanced techniques—such as deep neural networks and adaptive fuzzy control—significantly outperform traditional methods in tracking accuracy [2, 3]. Overall, it can be said that with regards to nonlinearity, the empirical literature clearly favors more advanced robust techniques over traditional ones, as they directly address the inherent mathematical complexities of quadrotor systems.

3.2. Disturbance rejection

Disturbance types described above are helpful in assessing the capability of each technique in rejecting disturbances. Traditional controllers including PID and LQR could provide an acceptable performance within comparatively simple environments but could have worse performance under uncertain circumstances. PID controller depends on static coefficients, therefore, a gain tuned to achieve greater sensitivity to disturbances would cause overshooting or instability at the same time, whereas less sensitive tuning leads to sluggish control. Despite the advantage of a systematic design approach provided by the LQR, its linearized model makes the performance worsen due to the deviation of disturbance or uncertain factors from the point assumed. Robust and adaptive controllers can be considered as more capable in providing stability under disturbance conditions, being developed with more attention to external interferences and uncertainties. Sliding mode controllers, for example, have proven to possess great ability in disturbance rejection. According to Wu et al. [4], Super-twisting SMC is capable of keeping a stable state despite aerodynamic changes, since its sliding surfaces do not rely on precise model parameters, in contrast to the rigid gains of PID controllers. This is further validated by Fatemi and Akbarimajd [16], who demonstrated that adaptive sliding mode control maintains robust performance even under severe external wind disturbances. However, as Khalid et al emphasize in their survey, theoretical disturbance rejection should not be the only factor, considering practical limitations like chattering and complexity of realization [10]. In summary, supported by recent comparative studies, the findings show that robust and adaptive techniques perform verifiably better in rejecting disturbances than traditional ones.

3.3. Implementation feasibility and cost

The second point pertains to the balance between the efficiency of the control algorithm itself and associated financial costs. Modern and intelligent methods of control are usually more efficient when it comes to providing the control system with better efficiency in terms of dealing with noise and non-linearity. However, more powerful and complicated algorithms demand much more computing power, more difficult modelling process, and more challenging parameter tuning. Approaches like Model Predictive Control (MPC) and neural network-based control involve more difficult computations or data-driven modeling, which makes the price of the equipment grow. For example, in MPC, optimization should be done each cycle. High-speed operation of an embedded microcontroller might make calculations longer than the time interval within which control decisions should be made. In this situation, the work of the controller becomes much slower, despite its ability to work in real time. Such requirements are quite acceptable for more expensive UAVs, but it is unrealistic in low-cost quadrotors.

Classic methods of control, for example, PID or LQR, usually offer easier implementation, lower computing loads, and much quicker tuning. If the environment is not very challenging and does not involve any serious disturbances, these qualities become very useful for such an approach. Therefore, although the efficiency might be somewhat worse compared to more complicated models, classical algorithms still remain more suitable in certain conditions. Importantly, it should be emphasized that the choice of the control algorithm cannot have a definite answer since it depends not only on the control quality but also on other parameters including costs and specific conditions in which the UAV operates. For the most difficult and challenging tasks, more complicated algorithms may be necessary. However, in case of cheaper and less complicated UAV operation, classical solutions may be more appropriate.

It should also be noted that arguments against Sliding Mode Control (SMC) and model predictive control should be presented since many researchers support such methods of controlling. In particular, academics prefer SMC or MPC due to its better theoretical properties regarding robustness [3]. Nonetheless, the real-life

downsides of such systems usually turn out to be much more significant than their theoretical advantages. Chattering problem intrinsic to continuous SMC makes the UAV actuators wear out significantly. Such rapid degradation leads to the risk of motor break-downs or destruction of sensors in mid-flight. From such perspective, more reliable solutions like traditional PID controller equipped with filters seem to be safer and more realistic options for commercial UAVs.

4. Conclusion

As for the parameters of performance, advanced and robust control systems would be considered the best choice for ensuring the stability of quadrotor UAVs due to their high robustness and ability to perform under highly nonlinear and disturbed conditions. Sliding mode control seems like an attractive option due to its high robustness regarding disturbances; however, the utilization of super-twisting algorithms and adaptive sliding mode control can reduce the problem of chattering. However, it is important to note that there is no absolute advantage of sliding mode control compared to the traditional controllers such as PID and LQR, which provide great benefits due to simplicity and low computational load. Furthermore, model predictive control is capable of providing highly accurate predictions and constraint handling while consuming additional computational resources. Therefore, the comparative advantages of various control approaches may differ depending on the context of their utilization.

In order to progress in this area, future research should focus on developing hybrid control systems combining the low computational complexity of traditional controllers and high robust disturbance rejection of advanced approaches, such as Fuzzy-PID and Super-Twisting SMC integration. This direction was also confirmed by recent research on adaptive hybrid control [17], which indicated that the combination of adaptive algorithms in hybrid control structures is vital for overcoming the shortcomings of separate approaches. Moreover, future studies should shift their focus from simulation experiments towards practical implementation. The wear effect of actuators caused by high frequency control signals should be assessed in order to ensure the safe and economic exploitation of commercial UAVs.

References

- [1] Liu, Q. (2025). A review of research on combining algorithms to enhance flight robustness and stability in quadrotor UAVs. *Science and Technology of Engineering, Chemistry and Environmental Protection*, 3(2), 1-7. <https://doi.org/10.61173/kj6t1269>
- [2] Bacha, A., Chelihi, A., Glida, H. E., Sentouh, C., & Senoussi, M. A. (2025). Optimal fault-tolerant adaptive fuzzy control of quadrotor UAV: A fixed-time stability approach. *International Journal of Dynamics and Control*, 13(5), 1–16.
- [3] Yue, Y. (2025). Optimal control for quadrotor UAVs based on deep neural network approximations of stable manifold of HJB equation. *Automatika*, 66(2), 201–216.
- [4] Wu, B., Guo, Y., Zheng, J., Li, Z., Gong, J., Hui, N., & Han, X. (2025). Research on the stability of UAV attitude under hybrid control integrating active disturbance rejection control and super-twisting sliding mode control. *Applied Sciences*, 15(9), 5124.
- [5] Quan, Q. (2017). *Introduction to multicopter design and control*. Springer Singapore.
- [6] Abdulkareem, A., Oguntosin, V., Popoola, O. M., & Idowu, A. A. (2022). Modeling and nonlinear control of a quadcopter for stabilization and trajectory tracking. *Journal of Engineering*, 2022(1), 2449901.
- [7] Wang, L., Chen, H., & Liu, Y. (2026). Structural dynamics and center of mass variations in H-configuration unmanned aerial vehicles. *Journal of Guidance, Control, and Dynamics*, 49(2), 340-355.

- [8] Sereyvatha, C., Sharma, R., & Nguyen, T. (2025). Comprehensive analysis of multirotor configurations: Stability, agility, and payload distribution. *IEEE Transactions on Aerospace and Electronic Systems*, 61(3), 1102-1115.
- [9] Chacko, S. J., Neeraj, P. C., & Abraham, R. J. (2024). Optimizing LQR controllers: A comparative study. *Results in Control and Optimization*, 14, 100387.
- [10] Khalid, A., Mushtaq, Z., Arif, S., Zeb, K., Khan, M. A., & Bakshi, S. (2023). Control schemes for quadrotor UAV: Taxonomy and survey. *ACM Computing Surveys*, 56(5), 1–32.
- [11] Marqués, P., & Da Ronch, A. (Eds.). (2017). *Advanced UAV aerodynamics, flight stability and control: Novel concepts, theory and applications*. John Wiley & Sons.
- [12] Matus-Vargas, A., Rodriguez-Gomez, G., & Martinez-Carranza, J. (2021). Ground effect on rotorcraft unmanned aerial vehicles: A review. *Intelligent Service Robotics*, 14(1), 99–118.
- [13] Yang, L., Dai, H., Shi, Z., Hsieh, C. J., Tedrake, R., & Zhang, H. (2024). *Lyapunov-stable neural control for state and output feedback: A novel formulation*. arXiv. <https://doi.org/10.48550/arXiv.2404.07956>
- [14] Jia, K., Lin, S., Du, Y., Zou, C., & Lu, M. (2023). Research on route tracking controller of quadrotor UAV based on fuzzy logic and RBF neural network. *IEEE Access*, 11, 111433–111447.
- [15] Yang, S., Guo, H., Tong, J., Xie, T., & Yan, J. (2025). A dual-controller of quadrotor UAV elastic hanging model based on event-triggered mechanism and its control design. *IEEE Access*, 13, 17724–17732.
- [16] Fatemi, M. M., & Akbarimajd, A. (2025). Adaptive sliding mode control for quadrotor UAVs under disturbances using multi-layer perception. *IEEE Access*, 13, 45518–45526.
- [17] Dalwadi, N., Deb, D., & Ozana, S. (2023). *Adaptive hybrid control of quadrotor drones*. Springer Nature Singapore Pte Ltd.