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Comparison of Various Control Techniques Applied to a Quadcopter

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ABSTRACT

A quadcopter is considered one of the most well-known examples of unmanned aerial vehicles (UAVS), because it has more advantages than standard helicopter in terms of size, efficiency, and safety. As a result, researchers are quite interested in it. In this paper, practical applications and various control techniques of the quadcopter are presented. This article summarizes an overview of quadcopter popular control strategies such as intelligent PID techniques, feedback linearization techniques, linear quadratic LQR techniques, sliding mode control techniques, and backstepping techniques, followed by analyses, pros, and cons of each control technique. The adaptive/observer-based augmentation of each nonlinear control technique is also discussed. Finally, our research prospects that the most important features of research and development quadcopter's future research will be directed by this focused literature. For each technique, the target and type of test of each research article are stated, making it easier for the researcher to select the research papers that best meet his objectives.

Keywords: Nonlinear Control, Quadcopter, Regulation, Tracking, Underactuated System.

1 INTRODUCTION

Unmanned aerial vehicles UAVs are small, unmanned aircraft that can be operated remotely by a human or be autonomous. It started as advanced technology and was developed by the army to be suitable for military applications, but now it is used in several applications spread over all fields of life. A quadcopter is considered one of the most popular examples of small-scale UAVs. It is also called a quadrotor system or drone. It has several application areas such as rescue[1, 2], military operations[3–5], and in agriculture for crop spraying pesticide [6, 7], therefore it has received considerable research attention.

In recent decades, the use of (UAVs) has become very common and vital, because it has more advantages than standard helicopter in terms of size, efficiency, and safety. One of the most important reasons that made the quadcopter distinct from the helicopter is its use of multirotor. There is no need for a swashplate since multirotor are generally controlled by altering the angular speed of the rotors, which simplifies not only the mechanics but also the system's maintenance [8]. When vehicles fitted with a failsafe controller, multirotor can also continue to fly following an actuator failure. Although the failsafe controller is easier to construct for multirotor with six or eight rotors, certain controllers were also created to handle a quadrotor actuator failure. The following papers provide examples of failsafe quadrotor controllers[9, 10].

The quadcopter system involves various complexities, therefore controlling it is a challenging task. The quadcopter model is, first and foremost, the nature of a quadcopter system is nonlinear. Second, the system has six degrees of freedom (DOF) but only four actuators, making it underactuated. Underactuated systems have a fewer number of control inputs than the degrees of freedom of the system. Because of the nonlinear coupling between the actuators and the degrees of freedom, they are extremely hard to control [11]. Third, it necessitates a big convergence zone and quick control response. Fourth, several quadcopter characteristics like as inertial moments and aerodynamic coefficients that are difficult to measure or estimate with high precision. Finally, due to its tiny size and weight, a quadcopter is highly susceptible to external disturbances[12].

For quadcopters, many control systems have been proposed for both regulation and trajectory tracking. The objective is to develop a control method that allows a quadcopter's states to converge to any set of reference states that change over time. Linear control methods such as linear PI not suitable for nonlinear system[13]. When nonlinearity is considered, the convergence zone expands. Also, controller development requires the development of a mathematical model of quadcopter dynamics. The dynamic model is obtained using either Newton-Euler method or Euler-Lagrange method [10].

This survey aims to give a deep understanding of various issues and compromises taken in the design of quadcopter controllers. It aims to give a thorough understanding of quadcopter related challenges. Existing flight control systems are investigated for potential benefits and drawbacks, type of test and type of target.

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2 REVIEW AND LITERATURE DISCUSSION

Several control algorithms for the quadcopter have recently been presented. To address with the quadcopter control challenge, many control techniques have been used. This problem has been solved using linear control approaches such as PID control and LQR[13-15].The stability of these techniques, on the other hand, is only assured in a limited scope. In compared to linear control methods, nonlinear control techniques can significantly broaden the stability domain.

An overview of typical quadcopter control algorithms is offered. The benefits and drawbacks of five different control techniques are examined.

2.1 Intelligent Proportional Integral Derivative Techniques

The traditional PID controller has a straightforward structure that is simple to construct. It offers high performance and easy to adjust constants, making it a popular choice for full actuated systems. Traditional PID controllers do not appear to be suitable for quadcopters due to the nonlinear nature of the quadcopter system, but some researchers have worked to adapt the controller to meet the attributes of nonlinear quadcopters. For example, in [17], the PID controller is formed from two subsystems: A fully-actuated subsystem that is controlled on altitude (z) and the yaw angle, and an underactuated subsystem that is controlled on X and Y position with the pitch and roll angle. This controller does not consider the gyroscopic effect and also ignored the effect of friction with the air. A nonlinear PI controller was proposed based on the classical PID technique in [18]. The authors succeeded to regulate the position and attitude with a satisfactory error. The X and Y position is controlled by PI controller, while the quadcopter attitude and altitude are controlled by PID algorithms. Furthermore, performance on quadcopter movements had been improved. The controller acts well against Coriolis forces and aerodynamic drag effects, even though just the gravitational influence is compensated. The validity of this controller is assessed in Matlab simulations. These designs had some flaws, such as disregarding air resistance and external disturbances.

With the emergence of the idea of intelligent control, many controllers appeared that overcome the problems of the traditional controller, such as the fuzzy PID controller, and neural network PID controller. The fuzzy PID controller technique merges the ideas of fuzzy control with classical PID controller, which can improve the response of the PID controller, which results in high control accuracy, good adjustability, and ease of implementation, but the deficiency is some steady-state errors. For example, the authors in [19] proposed classical PD and Hybrid Fuzzy PD controllers to test how fuzzy algorithms are suitable for controlling compared with the classical PD controllers. This hybrid controller had a good effect, reducing the impact of external turbulence, improving the durability of the system, and making it more flexible for the quadcopter system. It assured succusses in controlling the quadcopter compared to the classical one, and the gyroscopic effect was considered, also it had been tested experimentally. In [20], the authors introduced two models (PID controller and self-tuning PID), which are based on fuzzy logic.

To achieve a better control steady state error effect and overcome the problems caused by using the classical controller, a combination of classical PID and a neural network controller is introduced. Through the advantages of this controller, most of the problems were faced in controlling a quadcopter system have been overcome. To improve quadcopter control and reduce nonlinearity and uncertainty, a neural network controller is devised that uses a PID feedback controller and sets PID parameters online in [21]. The authors proposed a fuzzy radial basis function (RBF) neural network PID control system for a quadcopter to achieve good control performance in [22]. In [23], the authors proposed a PID controller to control the attitude and achieve stability. The PID's coefficient gains are adjusted from the lowest to the highest value until the coefficients match the optimal response. Also, the controller had been tested experimentally and by simulation analysis. Recently, new PID control designs are proposed to be suitable for quadcopter systems. This controller is used to adjust the control parameters of PID controller. The authors in [24], compared the performance of direct inverse control artificial neural network (DIC-ANN) with the PID control system. This model achieves automatic path tracking and reduces the influence of external disturbances. A waypoint navigation controller was proposed in [25], using the fuzzy PID controller. Results prove that the fuzzy PID controller can control the quadcopter to move to the desired position with low overshoot and low steady state error. In [26], the authors proposed a control technique that uses a genetic algorithm to optimize the back propagation artificial neural network (BPNN) tuning and PID control parameters, which addresses the issue that classical PID control parameters cannot be well adjusted with external disturbance in the tracking control process. The outcomes indicated that the overall convergence speed was enhanced, as well as the quadcopter attitude tracking under external disturbances, which was improved and robust. When turbulent, it may rapidly converge on the appropriate route and avoid chattering, making it useful in practice. In [27], the authors propose a Moving Target-Tracking technique. The tracking technique uses the Fuzzy-PI controller to follow a moving target at different speeds and different times. In[28], under external disturbances and parameter uncertainties, the adaptive proportional integral derivative control (APIDC) system exhibited a good attitude and position tracking performance. It also reduces the chattering that occurred due to the usage of sliding mode control. In [29], the fuzzy PID controller is proposed instead of the traditional PID because it is better to determine adaptive gains which improve the fuzzy controller's performance compared with the classic PID. The results showed that the integration of the two models affect the performance of attitude tracking. In [30], the challenge of multiple quadcopter control is discussed, and it is demonstrated how PID controllers may be adapted to meet the interference augmented model. Tracking inaccuracy and control signal energy are significantly reduced via invasive and non-invasive strategies as compared to the case of ignoring the interference area by two quadcopters.

2.2 Feedback Linearization Techniques

The operation of transforming a nonlinear system into a linear system utilizing a nonlinear feedback technique rather than a small signal approximation is known as feedback linearization. The nonlinear feedback controller was designed using linear control system theory, although some elements were omitted to reduce the system effect. To use this controller, you must first understand the system model parameters; this is one of the most challenging aspects of the feedback linearization approach. For the quadcopter model, linear feedback techniques have recently been developed, although these controllers often overlook some aspects like air resistance and parameter uncertainties. For example, in [31], a feedback control strategy suggested an enhanced performance between the coupling of the states, but it was unable to manage Euler angles and altitude(z) due to the uncertainty of system interference. In [32], a nonlinear observer controller is used to predict wind speeds without the need for sensors, although it can only track attitude and altitude, not position. In [33] a full control system (observer–estimator–controller) is proposed. This method demonstrates the controller's durability and helps them to decrease the number of sensors required. The obtained results show that the predicted values are converging well and that the tracking errors of the required trajectories are acceptable. In [34], the authors combined the benefits of feedback linearization and GH∞ controller to control the quadcopter taking into account parameters uncertainty. An adaptive estimator is used to estimate the effect of external disturbances like wind; thus, this controller has high robustness. The necessity of complete state statistics is one of the key drawbacks of the feedback linearization technique. This necessitates needs to the creation of a separate observer/ estimator for the estimate of system states. Feedback linearization for quadcopters was achieved in conjunction with observer design in [35, 36]. The third derivative of output states is required for feedback linearization of a quadrotor model, as shown in [37], but in this work, the employment of an observer model restrains the third derivatives, making the control technique more applicable for nonlinear systems. Also, the authors proposed continuous position control for a quadcopter using observer feedback. The ellipsoid approach constrained the inaccuracy to a small enough region around the origin that the system was able to follow the target location even during very aggressive movements[38]. In [39], the authors proposed a quaternion FBL controller model for exponential attitude stabilization of quadcopter which is based on the compensation of the gyroscopic and Coriolis torques. Also, it used a PD^2 feedback technique, where the proportional action is a function of the vector quaternion, and the two derivative behaviors are dependent on the angular velocity and the quaternion velocity. The proposed model was tested on a small-scale quadcopter. In [40], a quaternion-based solution has been proposed to the problem of attitude tracking, without measuring velocity. It consists of an auxiliary dynamic system that uses its output to control the attitude with a quaternary unit representing attitude tracking error. The error signal between the auxiliary output system and the quadcopter unit tracking error can provide the necessary dampening that would have been obtained by using angular velocity directly. The suggested control strategy takes into account the problem of attitude control and ensures nearly global asymptotic stability. In [41], the authors introduced two types of nonlinear controllers, feedback linearization controller that uses input augmentation to address the underactuated problem that is developed with reduced dynamics to decrease the amount of higher order derivative terms in the model controller, and adaptive sliding mode controller for the quadcopter. In [42], the proposed controller relies on a common control strategy including feedback linearity to deal with the nonlinear dynamic behavior of the vehicle which involved an inner loop attitude controller and an outer loop velocity controller. It was tested experimentally, and it had been proven by simulation. In [43], the authors introduced a unit quaternion attitude and position regulator and ensure the asymptotical stability of the equilibrium point. Without decoupling, the suggested controller deals with both rotational and translational dynamic control. It's critical in some cases when decoupling the dynamic model from rotational and translational dynamics is challenging. In [44], feedback linearization is designed and implemented to control the attitude. Moreover, PID is designed and realized in trajectory tracking. This controller was tested experimentally and the suggested controller's efficacy was proved by simulation results. In[45], the authors used five various types of nonlinear feedback laws to stabilize the quadcopter based on bounded feedback controller elements to control the quadcopter roll and pitch angles. These five controls have already been applied on the Dragan Flyer quadcopter. In [46], the authors introduced a quaternion FB controller to solve the tracking problem of the quadcopter (attitude and altitude), considering external disturbance and parameter uncertainty. A collection of filters is included to present estimation for the unmeasurable quadcopter variables and signals. In [47], the authors described a nonlinear model to stabilize the attitude and track the position of the quadcopter. The proposed model is successfully applied to the quadcopter. Simulation and experimental results indicate good performance for this controller. In [48], two sub-controllers (feedback linearization and two PD controllers) were used to control a quadcopter. The proposed model can simultaneously combine tilting and movement along the desired trajectory. The validity of the overall control system is proven by simulation. In [49], to take into account the external issues facing the quadcopter, the authors developed a unit quaternion attitude and altitude tracking system for a quadcopter. Semiglobal asymptotic tracking results were achieved using Lyapunov-based stability analysis. In [50], the authors demonstrate how a simple technique may be used to correct many sources of issues without using adaptive parameter estimates. Semiglobal asymptotic tracking is also accomplished. In [51], the authors proposed a feedback linearization approach to control quadcopters. They selected an optimal quadratic regulator as a linear control. This method had been proven to control the attitude of the quadcopter system successfully by the simulation results. In[52], the authors proposed a model based on feedback linearization side by side with backstepping. The proposed model presented satisfying results under high-acceleration trajectory tracking and slowly varying wind conditions. In [53], model disruptions, imprecision, and uncertainty may be resolved via feedback linearization and LQR approaches, that can follow a predetermined trajectory and display sustained position error. Their technology was successfully tested in a simulation before being put into action on a quadcopter. In[54], feedback controller for attitude and altitude regulation of a quadcopter is proposed. Global asymptotic stability of the designed controller is verified using Lyapunov stability criterion.

2.3 Linear Quadratic LQR Techniques

The LQR control technique is regarded as one of the most effective controllers for dealing with a dynamic system while minimizing costs and mistakes. Because of its endurance and high performance, it's a suitable comparison control tool if some assumptions are made. In LQR techniques a quadratic objective function is minimized over controller parameters to minimize an error term. In [55], the authors presented attitude controller by using LQR model with a full-order observer. A real-time controller technique for autonomous collision-free operations was proposed for the quadcopter. The simulation results had proved the feasibility of this controller and showed that the quadcopter model tracks the trajectories generated in real-time despite wind friction and other perturbations, but this controller needs improvement to be suitable for applications that have more than one quadcopter. In [56], linear quadratic (LQ) and linear quadratic gaussian (LQG) with integral action controller had been proposed to stabilize and proceed with the output-tracking objective. To determine the position and attitude of the aircraft, the dual camera method is used. Simulation results proved the ability of the controllers to execute output tracking control objectives in hovering. LQR controller in [57], is suggested to estimate state variables utilized in the controller design instead of needing a sensor. In [58], after linearizing the quadcopter model, simultaneous control of the quadcopter and the manipulator are achieved via LQR controller. Finally, unscented kalman filter (UKF) LQR technique is proposed to achieve state estimation of the system. Simulation results showed the feasibility of the proposed approach. The authors in [59], made a hybrid model consisting of PID technique and LQR technique to achieve position tracking for quadcopter system. They used differential flatness-based feed forward control to improve the performance of the proposed controller for tracking the complex trajectory efficiently. Also, in [60], the quadcopter position was stabilized using feedback linearization and LQR controllers. Feedback linearization responsibility is correcting any errors that occur. To increase the control algorithm's performance, the LQR controller was integrated with the feedback linearization model. In [61], a quadcopter LQR model controller has been built. The findings validated the controller's validity and demonstrated that the model dynamics effectively respond to the directed inputs. In terms of settling time, overshoot, and reaction time, the suggested controller was able to achieve the performance requirements. It was also put to the test under various settings, as well as the impact of the Q and R weighting matrices on the K feedback gain matrix. The controller's reaction was faster for lower values of K, although there were some concerns with settling time and overshoots. In addition, it was discovered that the controller's stability is dependent on the correct tuning parameter of the gain matrix K. In [62], LQR controller is proposed to control the position and yaw angle of the quadcopter. A simulation was performed to analyze the performance. It was noticed that steady-state error in altitude can be reduced by applying integral feedback in the developed model. Double derivative-linear quadratic regulator (PD2-LQR) controller is presented in [63]. The suggested PD2-LQR controller's results were compared to the PD, PID, LQR, P-LQR, and PD-LQR controllers. The results show that the suggested PD2-LQR controller greatly enhances the control system's performance in all responses.

2.4 Sliding Mode Variable Structure Control Techniques

The sliding mode controller (SMC) has the benefit of solving uncertain issues. This method adjusts the quadcopter's error and deviation for the suggested controller to follow the required trajectory. The control signal's switching and discontinuous characteristics were employed to change the dynamics of the nonlinear system under control. There are two types of SMC; the first type takes care of designing a sliding surface that is suitable to the required movement constraints and the second type is concerned about control law which will force nonlinear system states towards sliding surface. Once the system reaches this surface, it will be close to the equilibrium point. The surface is chosen such that it provides at least an asymptotic stable origin, however, exponentially stable origin with limited settling time is desired. SMC controller belongs to a variable structure control type. The control signal's switching and discontinuous characteristics were employed to change the dynamics of the nonlinear system under control. While all these problems, SMC offers rapid response and relatively good robustness with uncertainties and external disturbance problems compared to other algorithms.

Many studies have recently created a variety of controller designs to improve sliding mode designs. For example, in [64], the authors presented a model formed of subsystems that were both underactuated and fully actuated. The chattering effect was reduced by using a continuous approximation of the signum function. This model can achieve the desired position and yaw angle, as well as regulate pitch and roll angle at zero. When uncertainty is added to each parameter, only altitude is affected greatly because PID controller is used to control altitude Z, which is sensitive to the parameters change. While the X and Y horizontal position, and yaw angle are not affected. In [65], the authors proposed a study, in which quadcopters face external disturbances and actuator failure. The controller can restrain external disturbances and can differentiate between external disturbances and actuator fault. Various simulations had been performed to prove the good performance and effectiveness of the proposed model. The authors propose sliding mode control with a sliding mode disturbance observer (SMC-SMDO) in [66]. The system's robustness to the changes caused by external disturbances and model uncertainty was improved. Furthermore, the controller can swiftly correct for changes in external disturbances without resorting to high-power gain. In addition, the multiple-loop, multiple time scale SMC-SMDO is developed to successfully regulate the quadcopter's position and attitude while just requiring knowledge of the disturbances' boundaries. Also some sliding mode studies have been covered, as well as observer design[67–69]. The estimation of system states and disturbance rejection are both aided by such observer setups. Altitude control is a difficult task due to many factors such as its directly coupled dynamics relevant to the mass of the quadcopter, the angle of rotation, the effects of wind, and sudden change in the mass of the aircraft [70]. Three second order sliding mode controllers are proposed to track the altitude to overcome these issues. The three controllers were compared to know the best of them, and it was concluded through the results that twisting SMC has the least error. Also, the three controllers were tested experimentally. In [71], the authors developed adaptive sliding mode control based on feedback linearization, which is effective against quadcopter ground effects. The asymptotic stability of the overall system was assured based on the Lyapunov stability methods. The effectiveness of the proposed method for quadcopter systems with ground effects was demonstrated. The proposed model achieves a good performance under different regulation tasks, gain variations, and external disturbances. Experiment results further demonstrate the control model's durability and stability. The SMC provides robustness with uncertainties and external disturbance problems, but it needs knowledge of the upper bounds of uncertainties, due to this reason, an adaptive sliding tracking controller in [72] was proposed. It does not need the upper bound of the uncertainties to achieve a low tracking error compared to the classical sliding mode controller. Attitude and altitude tracking controller which is based on a combination of sliding mode technique and PID technique is proposed in [73]. This controller offers fast adaptation and the rigorous flight control robustness of the quadcopter under the influence of turbulence. The proposed model is compared with four states of the art to demonstrate its effectiveness. In [74], the authors built a simplified model in the presence of air disturbances. Then, they proposed an attitude controller via backstepping-SMC of the quadcopter. Afterwards, they proposed an integral SMC to track the position in the presence of disturbances. In the face of uncertainties and random disturbances, a novel sliding-mode controller was designed to handle the quadcopter trajectory in [75]. They also created a one-of-a-kind time-varying sliding mode surface to eliminate phase error, reduce initial control effort, and meet the impact time requirement while employing a global sliding mode.

2.5 Backstepping Design Techniques

The backstepping design's fundamental principle is to represent the dynamic system in multiple stages while developing the control rule. This technique is based on the Lyapunov criterion to be suited for underactuated systems. It's a recursive method that starts with a known stable subsystem and progressively converges the outer subsystems with each subsequent controller. This process continues until the beginning of the real control term, backstepping gets its name from this. If all states cannot be measured, an observer must be designed. Backstepping controllers have several problems, such as limited system resilience, although some techniques may be used to overcome these problems. For example, the authors suggested a backstepping control technique in [76], which can stable a quadcopter's position and yaw angle to the desired trajectory. This controller consists of three interconnected subsystems. The first subsystem is responsible for the horizontal movement (X, Y) by controlling the pitch and roll angles; it is an under-actuated subsystem. The second subsystem is responsible for controlling the altitude (Z) and the yaw angle; it is a fully actuated subsystem. The last subsystem handles the propeller dynamics. The simulation results demonstrated that the proposed control strategy performed well. In [77], a quadcopter was stabilized using a sequential nonlinear method controller. For the translational subsystem, feedback linearization was integrated with a PD controller, and for the quadcopter's rotating subsystem, a backstepping based PID nonlinear controller was used. Simulation results show that the suggested controller has a good performance in semi stationary flights. Among the preferred techniques, solutions relying on a backstepping control technique that utilizes quaternion representation. The validity of the proposed controllers is verified by simulation and Lyapunov stability criterion. A trajectory tracking controller for the position and yaw angle of a quadcopter was proposed in [78], which is based on quaternion representation. Attitude parametrization was divided into two rotations. The orientation of the thrust vector is described via the first rotation, while the second rotation describes the yaw angle. These rotations are decoupled from each other. As a result, all control signals were deduced analytically at a reasonable cost. Maximum convergence rate attitude controller was proposed under the constraint of input saturation in [79] based on quaternion representation. As a result of the difficulty in finding closed form solutions to the Hamilton Jacobi Bellman (HJB) equation, the inverse optimal approach solution was used. Global asymptotic stability of backstepping based inverse optimal attitude controller (BIOAC) controller was verified using Lyapunov stability criterion. This controller had also been experimentally tested. The BIOAC controller had been compared with a classic PD controller, and the results show that BIOAC achieved faster convergence while reducing the control effort. A quaternion command filtered backstepping controller was proposed in [80], to control the position and yaw angle of the quadcopter. Quaternions have their unique algebra, so a vector-based command filter cannot be used; therefore, second-order quaternion filter was used with its derivative, which determines the commanded angular rate vector. Global asymptotic stability was verified using Lyapunov stability criterion. A hybrid controller using feedback and integrator backstepping was proposed in [81], based on quaternion representation. This controller was based on offsetting the torque of the Coriolis and the gyroscope. Asymptotic stability was proved via Lyapunov stability analysis with an adequate choice of integrator backstepping variables, in the presence of external disturbance. Also, two controllers were presented in [82], to track the attitude and the altitude of the quadcopter based on a multiple-input multiple-output (MIMO) system for inner loop controller in the presence of the external disturbance and uncertainties model. For the outer loop controller, the first one is the sliding mode technique while the second is backstepping technique. Then, feedback and LQR techniques were proposed to track the position of the quadcopter. Both controllers were compared, and the backstepping controller proved effective under different conditions. Another tracking controller based on multiple input multiple output (MIMO) systems was presented in [83], based on the backstepping technique to track the position and yaw angle of the quadcopter. The semi-global stability was proved to be guaranteed while reducing tracking errors as small as desired with expected convergence rate, also this controller was experimentally tested, and its effectiveness was proved. Backstepping control method was proposed to achieve finite-time convergence of error states to the origin in [84], by using Lyapunov stability criterion for a group of quadcopters. To track the position and attitude, an adaptive tracking controller via the backstepping technique was proposed in [85]. The backstepping technique was used to track the position and the orientation while the adaptive law was used to find various unknown parameters like arm length, inertial moment, and drag coefficients which are difficult to be accurately calculated in practice. Asymptotic stability was proved via Lyapunov stability analysis. Another adaptive controller was proposed in [86] to solve the problem of path tracking within uncertainties. Furthermore, it was also made robust against the external issues and changing perturbations over time by designing perturbation estimators. Lyapunov stability analysis, simulation analysis, and experimental prototype are used to check the validity of this controller. In [87], by using the Euler angle orientation representation, a backstepping controller is developed to manage the altitude and orientation of quadcopter systems. Also, the Lyapunov function ensures the controller's validity, and simulation results revealed a high-precision transient and tracking response. Although there are errors in the model, a neural network-based backstepping controller for quadcopter tracking has been proposed in [88].

This technique has been used by several researchers to create a quadcopter flight controller. The necessity of full information of all system states is the key restriction of this technique when implemented on a real time quadcopter. When it becomes impossible to measure all the states, it is unavoidable to construct an observer, especially, in high-speed motion control applications requiring great accuracy.

3 COMPARATIVE REMARKS

A lot of research has been conducted regarding the control of the quadcopter, and many techniques have been used to control it. In this work, the focus has been on the five most common methods. The advantages and disadvantages of these techniques have been presented in Table.1. Simulation, Lyapunov function, and experimental tests were used to verify the validity of the controller, which was listed in each technique, type of test, used to prove the validity of the proposed controller in Table.2. Several control algorithms have been proposed for quadcopters for several targets as shown in Table.3. There are several ways to represent the orientation of a rigid body in relation to an inertial frame. Such representations contain rotation matrices, Euler angles, and quaternions. The rotation matrix representation uses nine parameters, the orientation is over-parameterized. Also, the Euler angle representation requires just three parameters to indicate orientation, it is a common choice for describing orientation in controller design. However, there are several disadvantages to using the Euler angle representation. Singular configurations of the Euler angle representation exist, in which the angular velocity loses one degree of freedom. The use of a four-parameter form, particularly unit quaternions, can overcome these limitations. Despite this, it is less frequently used compared to Euler angle representation.

4 CONCLUSION

To date, several control algorithms have been proposed for quadcopters, each with advantages and disadvantages. The most prominent control algorithm for quadcopters must conform to the real design requirements to achieve the best control performance. The investigation of control algorithms in quadcopters should be carried out under the following main considerations: algorithm-based controllers must have good dynamic performance; the uncertainty of model parameters, and air friction. The steady-state response should be unaffected by noise interference and other uncertainty. Also, controller design should be simple as possible easy to implement. The practice has shown that the single flight control algorithm can no longer meet all requirements for a good performance controller. The combined use of multiple algorithms is a forthcoming trend, but its complexity is unable to ensure the robustness and fault tolerance of the control system. The difficulty in using the flight controller lies in how to compromise between dynamic performance, steady-state behavior, and controller complexity.

Table.1: The advantages and disadvantages of common control algorithms for quadcopter.

Name of Common Control Technique	Advantage	Disadvantage
Intelligent PID	The structure of the controller is simple. The robustness and reliability are strong. The controller has self-learning and self-adaptive benefits, and an accurate model is not required.	For fuzzy control PID: A significant steady state error exists while for neural network PID: convergence speed is slow.
linearization Feedback	The controller design is flexible and easy to implement.	Accurate modeling is required. It is not robust against external disturbance.
Linear Quadratic LQR	The controller design is simple and easy to mount in a closed loop.	It is a linear control technique and lack robustness of a non-linear model.
Sliding mode control	Quick response controller; doesn't need accurate model; not sensitive to external disturbances.	Easy to lose balance at a point close to the equilibrium point.
Backstepping	Good robustness under external uncertainty.	Low system robustness.

Table. 2: Type of test of common control algorithms for quadcopter.

Name of Common Control Technique	Reference	Type of Test		
		Simulation	Lyapunov	Experimentally
Intelligent PID	[19], [23], [24-25], [27], [30].	✓	Na	✓
	[17-18], [20-22], [26], [28-29].	✓	Na	Na
Feedback Linearization	[31], [33],[35-36], [43], [44], [48], [51].	✓	Na	Na
	[32], [34],[37], [39], [41-42], [46], [49-50], [52], [54].	✓	✓	Na
	[38],[45], [53].	✓	Na	✓
	[47].	✓	✓	✓
Linear Quadratic	[55-63].	✓	Na	Na
Sliding Mode	[65 -67] .	✓	Na	Na
	[64] ,[68- 69], [71 -75].	✓	✓	Na
	[70].	✓	✓	✓
Backstepping	[76-77], [80-82], [84-85], [88].	✓	✓	Na
	[78- 79], [83], [86].	✓	✓	✓
	[87].	✓	Na	Na

Table. 3: Type of test of common control algorithms for quadcopter.

Name of Common Control Techniques	Reference	Type of control target			
		attitude	Yaw angle	position	altitude
Intelligent PID	[17], [20], [27].	Na	Na	✓	✓
	[18 -19], [21], [25], [28].	✓	✓	✓	✓
	[22], [26], [29].	✓	✓	Na	Na
	[30].	Na	Na	Na	✓
Feedback linearization	[31], [33-36], [38].	Na	✓	✓	✓
	[32], [37], [46], [49], [50], [52], [54].	✓	✓	Na	✓
	[39], [42], [51].	✓	✓	Na	Na
	[41], [43 -45], [47- 48], [53].	✓	✓	✓	✓
Linear Quadratic	[56], [58 -60].	✓	✓	✓	✓
	[57].	✓	✓	Na	Na
	[55], [62].	Na	✓	✓	✓
	[63].	✓	✓	Na	✓
	[61].	Na	Na	✓	✓
Sliding Mode	[64], [66], [67],[69], [71-72].	✓	✓	✓	✓
	[65],[68], [73], [75].	✓	✓	Na	✓
	[74].	Na	Na	✓	✓
	[70].	Na	Na	Na	✓
Backstepping	[77], [80], [82], [83 -85], [88].	✓	✓	✓	✓
	[76], [78],	Na	✓	✓	✓
	[79], [81].	✓	✓	Na	Na
	[86- 87].	✓	✓	Na	✓

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