Quadrotor Controller Design Techniques and Applications Review

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Abstract: *Rotor-craft style UAV, such as the quadrotor, has become increasingly popular with researchers due to its advantages over fixed-wing UAV. The quadrotor is highly maneuverable, can perform vertical take-off and landing (VTOL), and can hover flight capability. Nevertheless, handling the quadrotor complex, highly nonlinear dynamics is difficult and challenging. A suitable control system is needed to control the quadrotor system effectively. Therefore, this paper presents a review of different controller design techniques used by researchers over the past years for the quadrotor rotational and translational stabilization control. Three categories are discussed: linear controller, nonlinear controller, and intelligent controller. Based on their performance specifications, the system rise time, settling time, overshoot, and steady-state error are discussed. Finally, a comparative analysis is tabulated, summarizing the literature in the performance specifications described above.*

Key Words: *Quadcopter, Linear Controller, Nonlinear Controller, Intelligent Controller, Altitude and Attitude Control, Trajectory Tracking Control*

1. INTRODUCTION

The quadrotor can perform vertical take-off and landing (VTOL) in a confined area. Low cost, simple structure, and small size make the quadrotor useful in rural areas without runways [1]. A four-rotor propulsion system can carry a higher payload relative to its size. A quadrotor control system is complicated and challenging because its dynamics modelling is highly nonlinear, especially after accounting for the complicated aerodynamic effects. Its variables are highly interdependent and coupled in nature, which are controlled by only four independent inputs (rotor speeds). A precise controller design is needed to control the quadrotor system.

An effective attitude stabilizer is essential for maintaining the desired orientation. The speed of all four rotors of the quadrotor must be synchronized correctly. Controlling the quadrotor is not an easy task since it has a complex nonlinear dynamical system and coupled aerodynamics. Thus, a suitable controller is necessary to overcome these problems so that the desired performance of the quadrotor can be achieved. There are three different categories of flight controllers that are being used for controlling the quadrotor. These controllers can be categorized as 1) linear control, 2) nonlinear control, and 3) intelligent control.

2. LINEAR CONTROL

The linear controller is the most commonly used and successfully implemented in the early quadrotor development and today. It is proven to be efficient and capable of obtaining a stable flight condition. The complexity of this type of controller is low, making it easy to be implemented and a popular choice for industries. Nevertheless, three distinct types of linear controllers, namely PID, LQR, and H∞, and their variations, are reviewed in the following subsection.

Proportional-Integral-Derivative Controller (PID). PID controller is the most straightforward feedback controller most commonly used in the industrial application due to its simplicity [2]. The combination of Proportional, Integral, and Derivative controller gives several advantages which are easy to implement. Li, et al. [3] designed a PID controller to analyse the dynamic characteristics of the quadrotor to control the position and orientation of the quadrotor in 3D space. Their simulation found that the controller can achieve a stable and good response in all states even when disturbed by the wind. However, the system experiences a slight overshoot in all states. Castillo-Zamora, et al. [4] compared the PID, PD, and Sliding Mode controller (SMC) for position control of a V-tail quadrotor. They found that the SMC controller has faster stabilization time, but it produces a large pitch and roll angle that exceed 20°, which makes it unfavourable in real-world conditions. In terms of steady-state error, the PID and SMC controllers can eliminate the error while the PD controller cannot as time increases. Pan, et al. [5] conducted a study of an optimal PID controller based on the Qball-X4 quadrotor developed by Quanser company as experimental platform for the trajectory tracking control. Given tracking errors and delays, they designed a corresponding Kalman Filter to estimate the target trajectory. The finding shows that the system can reach the desired altitude height in an acceptable period without steady-state error but produces high overshoot.

Imane, et al. [6] conducted a study on the optimization-based PID controller to obtain an optimal gain parameter for the controller. They used the Reference Model (RM) method and Genetic Algorithm (GA) to optimize the gain of the PID controller for the altitude and attitude angle control. Both controllers have zero overshoot and steady-state error. Another nature-based optimization approach is presented in Erkol [7] to find the optimal PID controller gain for controlling the altitude and attitude angle of the quadrotor. In this work, a comparison between Artificial Bee Colony (ABC), Particle Swarm Optimization (PSO), GA, and traditional tuning Ziegler-Nichols (ZN) based PID controller was done. In terms of RMSE, GA is the best, followed by ABC, PSO, and ZN.

Ahmad, et al. [8] presented a comparative study of two classical PD and PID controllers for controlling the altitude and attitude angle of the quadrotor. Both controllers have a fast response within approximately less than 1 second in all states. The PD controller gives a better response in attitude control in settling time, which is 2 seconds. Burggräf, et al. [9] presented a cascaded P-PID controller that can control and stabilize the quadrotor attitude. The overshoot of the system is less than 25% in roll, pitch, and yaw motion, respectively. The controller can stabilize the quadrotor in just 2.2 seconds after being exposed to external disturbances such as wind and collision. Medjdoubi, et al. [10] proposed a nonlinear PID (NPID) controller used to control the altitude and attitude of the quadrotor. The controller gain can be optimally tuned by using the RM strategy. NPID gives a faster response time within 1-second compared to classical PID.

Linear Quadratic Regulator Controller (LQR). LQR controller is a type of feedback controller with an optimal control technique. The output of this system is feedback through the controller gain K [11]designed for closed-loop stabilization. A trade-off between the control effort and the transient response needs to be considered. Hernandez-Martinez, et al. [12] performed a study of trajectory tracking control of the quadrotor using a two-level control strategy to achieve maximum flight control time, energy-saving is addressed. The simulation result shows that the quadrotor can follow the desired trajectory with the desired value of the attitude angle.

Okyere, et al. [13] presented a step-by-step design of the LQR controller for controlling the altitude motion of the quadrotor. They found that if R is high, K will below, and the response will be slower and vice-versa. When K is higher, the state response is faster to reach zero, but the controller response becomes slower and produces a steady-state error. Zhi, et al. [14] proposed an optimal LQR controller combine with Kalman Filter to control the attitude angle of the quadrotor. The performance of the controller is then compared with a classical PID controller. Both controllers can meet the system requirement with no steady-state error under noise-free conditions. However, the LQR controller does not produce an overshoot and smoother response, while PID has a slight overshoot of up to 0.2°.

Martins, et al. [15] added a Kalman Filter to estimate the state of the quadrotor that relies on the measurement from motion sensors installed on-board. Overall, a good trajectory tracking was achieved, and the response converges to the desired point without error. Some error was observed in the yaw response, but it does not exceed 0.01°. Shah, et al. [16] provided a study of trajectory tracking control for the quadrotor using Gain Scheduled Integral LQR. The integral term is added to improve the tracking performance of the quadrotor by minimizing the steady-state error of the system. Based on their findings, the continuous gain control law can overcome chattering and discontinuity problem.

H∞ Controller. The H∞ controller is a robust control technique that can manage to deal with external disturbance and parametric uncertainty that arise in the system dynamics. The ability of the controller to eliminate the disturbance has made the controller become an effective control method [1]. An H∞ controller based on the Grey-Box method for model parameter identification was developed to control the attitude response of the quadrotor [17]. It was discovered that both controllers have 0.2 seconds in rising time and slight overshoot, but the H∞ controller gives better performance in reference tracking than the PID controller.

Rich, et al. [18] presented a robust H∞ controller for quasi hover conditions using the Glover-McFarlane loop shaping method. The controller can handle high bandwidth input changes without any problems and produces an aggressive pitch response when subjected to longitudinal movement.

Alkamachi, et al. [19] conducted a study based on modified quadrotor dynamics by adding a tilting mechanism to the propellers in their respective axes. The quadrotor successfully tracks the desired path, with only 2 cm drifted from the actual path.

The controller is efficient in eliminating the disturbance, sensor noise, and parametric uncertainty. Noormohammadi-Asl, et al. [20] presented a study of the H∞ controller for controlling the attitude of the quadrotor in the presence of parametric uncertainties in the system. They concluded that the controller has successfully realized the tracking, disturbance attenuation, and input saturation objectives.

3. NONLINEAR CONTROL

A variety of nonlinear controller has been studied and implemented on the real quadrotor platform by the researchers. In this subsection, some of the nonlinear controllers, namely Feedback Linearization, Backstepping, Sliding Mode Control, Adaptive Control, Active Disturbance Rejection Control, and Model Predictive Control, are discussed.

Feedback Linearization Controller (FL). Feedback Linearization is the commonly used control technique for controlling a nonlinear system. This technique can be design by converting the nonlinear system into a corresponding linear system by incorporating a suitable control input for the system. Bonna, et al. [21] presented a FL for a trajectory tracking control of a quadrotor. The position and the yaw angle of the quadrotors converge toward the desired reference trajectory within 5 seconds. They concluded that this technique gives the control designer more freedom to increase the performance of the controller at the cost of control effort. Chalidia, et al. [22] proposed a different control technique for controlling the rotational and translational system of the quadrotor. They developed two types of controllers with good response for autonomous vertical take-off and landing, namely Feedback Linearization to regulate/ stabilize the rotational motion and Fuzzy Takagi-Sugeno to control the translational motion of the quadrotor. Ye [23] presented a study of the FL to achieve attitude control and stabilize the quadrotor system. An Integrator was added to the Feedback linearization control system to reduce the tracking error.

Backstepping Controller. The backstepping control technique was developed for a class of nonlinear dynamical systems. It is a method for stabilizing the origin of a system in a strict feedback form. Huo, et al. [24] presented a backstepping control technique designed based on the compensation for Coriolis and gyroscope torque control law. Instead of using Euler angles to model the attitude system of the quadrotor, they used a unit quaternion formulation to avoid the singularity problem presence in Euler formulism.

Tripathi, et al. [25] conducted a comparative study of three controllers: Backstepping, Sliding Mode Control, and PID. They reported that the PID controller produces an overshoot in attitude response with larger settling time. The backstepping controller gives good control over the SMC since it produces a chattering effect. PID controller is unable to stabilize the system when operating outside a linear region. Overall, the Back Stepping controller can give better control in stabilizing the attitude and position of the quadrotor.

Basri, et al. [26] conducted a study on autonomous control of the quadrotor for stabilization and trajectory tracking using an optimal Backstepping control technique. They introduced an optimization tool, namely PSO, to compute the optimal control parameters of the Backstepping controller and proved that using optimization tools can quickly and efficiently get an optimal control parameter. They successfully stabilize the attitude angle of the quadrotor in the desired hover altitude position. As for a tracking problem, they realize the quadrotor can follow the desired trajectory quickly with small tracking errors and good tracking performance.

Lu, et al. [27] presented a new methodology in designing a Backstepping controller by using an online optimization technique for controlling the position and attitude of the quadrotor. They addressed the necessity to build a control strategy that can integrate both path planning and tracking control problems since traditional control design is only used to solve them separately. They suggest that the planning controller must first generate the obstacle-free trajectory online, then the tracking controller regulates an optimized system dynamically to achieve the newly planned path. Nevertheless, the precision of the controller attitude tracking angles and the quadrotor trajectory remains in an acceptable range in experimental work.

Saud, et al. [28] designed an Integral Backstepping controller to improve the steady-state error in the presence of disturbance using a PSO. Three simulation cases were conducted, first to move the quadrotor to a specific point in space while stabilizing the orientation angles of the quadrotor, second is to track a linear and curve path, and three to test the robustness against external disturbance. The proposed controller showed a robust performance when the external disturbance was added since the quadrotor can track the desired position without compromise.

Nguyen, et al. [29] presented a new method of designing a controller for the quadrotor to perform a trajectory tracking problem. First, Euler-Lagrange formalism was used to model the nonlinear dynamics equation of the quadrotor, where the translational motion was parallelly separated into vertical and horizontal dynamics. Then a tracking controller was conceived via the Backstepping control technique. An adaptive law was proposed to deal with system parametric uncertainties such as arm length, inertial moment, and a viscous coefficient that is usually hard to correctly calculate. Their findings include the quadrotor successfully tracks the desired trajectory with favorable tracking error that tends to converge to zero as time increase. They concluded that the method could remove the finite escape time if the dynamics models are separated into several subsystems and allow for a smooth altitude change. Asymptotic stability was achieved for the entire horizontal subsystem. The horizontal tracking error and suitable parameter estimator were stable. Compared to other studies, they verify that the proposed controller [29] is effective and gives superior performance for the path tracking problem.

Sliding Mode Controller (SMC). Sliding Mode Control is a nonlinear control technique that uses a discontinuous control signal to change the dynamics of a nonlinear system by forcing the system to move within the system normal behavior. A non-continuous function of time control law switches from one continuous structure to another based on the current position in the state space. Therefore, Sliding Mode Control is classified as a variable structure control method; it provides robustness against the model errors, external disturbance, and parametric uncertainties. However, the real implementation of the Sliding Mode Control is approximated with a high-frequency control signal that caused a chattering effect in the system due to the control switching between two structures.

Cömert, et al. [30] conducted a comparative study of SMC with a conventional PID controller to control the altitude and attitude angle of the quadrotor. The dynamic model of the quadrotor was formulated using the Newton-Euler approach, where a boundary layer around the sliding surface was introduced to assure that the chattering problem is eliminated. A sigmoid function was used for the altitude controller, and the saturation function was used in the attitude controller. The finding shows that SMC gives a faster response time and less oscillation when tracking the desired altitude and attitude angle compared to a PID controller.

Zheng, et al. [31] proposed a second-order SMC for the position and attitude tracking control of a small quadrotor. In this paper, the dynamic model of the quadrotor was divided into two subsystems, a fully actuated and an under actuated subsystem. The simulation result shows that the proposed controller can stabilize the position and attitude angle of the quadrotor within a second when abrupt changes in position and attitude motion are commanded. The tracking error converges to zero within a short time.

Mofid, et al. [32] presented the development of an adaptive SMC to stabilize the attitude and to track control of the quadrotor in the presence of model parameter uncertainties. Lyapunov stability theory and finite-time convergence were applied for the control method, guaranteeing the convergence of the quadrotor states in the finite-time. The simulation result shows that the proposed controller can track the desired state and stabilize the state effectively. It gives faster and more accurate transient response than other controllers. No chattering effect is observed in the control input with appropriate peak overshoot value. The sliding surface converges quickly to zero in finite time. The tracking error converges accurately to zero. However, slight chattering occurs when measurement noise is added.

Adaptive Controller. The adaptive controller is a type of control technique that adapts to the parameter uncertainties or unmodelled system dynamics. Parameter estimation is used in designing the adaptive controller that provides the updated law, which is then used to modify the estimated states in real-time. This updated law can be derived based on the Lyapunov stability theorem that defines the convergence standard. Mohammadi, et al. [33] presented a study of a decentralized adaptive controller based on improved Lyapunov based Model Reference Adaptive Control (MRAC) method in the presence of parametric and non-parametric uncertainties. In this paper, simulation and implementation of the real quadrotor system were conducted. The finding shows that the proposed controller can stabilize the quadrotor—the performance index, overshoot, and settling time of the proposed controller better than the PID controller.

Ghaffar, et al. [34] conducted a comparative study between the Model Reference Adaptive Control (MRAC) and the LQR controller for the altitude control of the quadrotor when picking up an object with unknown dimensions and mass. Both controllers experience some degradation in the tracking performance when the mass is added into the system. Still, the LQR performance shows a significant drop when reaching ground level, while MRAC only exhibits some oscillation around nominal altitude. However, both controllers regain their altitude afterward. MRAC can maintain excellent performance with minimal oscillation compared to LQR.

Xu, et al. [35] conducted a study to investigate the performance of L1 adaptive control concerning the actuator fault. L1 adaptive control can provide a fast adaptation rate by using a high gain in the adaptation block, which can benefit from performance and robustness. The L1 adaptive control provides a better performance than the integral LQR controller. Also, L1 adaptive control can manage with intermittent failure better than an integral LQR controller with lower oscillation and smaller deviation.

Active Disturbance Rejection Controller (ADRC). ADRC is a nonlinear feedback controller that does not need an accurate mathematical model of the system. The total perturbation or virtual state is estimated by the Extended State Observer (ESO) and used in the control system. In this way, the effect of uncertainty in the model is compensated in real-time. This method gives a better solution if the full knowledge of the system is not available. The ADRC controller consists of three components 1) tracking differentiators that solve the trade-off between the rapidity and the overstrike, 2) ESO that observes the state of the system and external disturbance, and 3) nonlinear state error feedback.

Dou, et al. [36] presented a study of altitude and attitude control of the quadrotor under internal and external disturbances using ADRC. Here, a dynamic surface control algorithm was used in designing the controller based on the estimated states by ESO to ensure the robustness and adaptability of the system with uncertainties and external disturbances. The proposed controller successfully tracks the disturbance in each subsystem effectively, even with the sudden change in the disturbance. The controller can track the desired path rapidly with excellent tracking performance under disturbance, and ESO can estimate new states in a short time. A comparative study between the traditional ADRC and the ADRC-SMC shows that the proposed controller has better stability and robustness under internal and external disturbance than others with better tracking performance and smaller overshoot.

Zhang, et al. [37] presented a study of a double close-loop ADRC scheme for trajectory tracking control of the quadrotor under external disturbance. They adopted the ADRC scheme in both attitude and position loop. A comparison with the PID controller was made to see the performance of the proposed controller in two simulations with a different trajectory pattern. The finding shows that ADRC can provide a better tracking performance with faster response and high accuracy than the PID controller in both simulations, even in the external disturbance. The error of ADRC is lower than the PID controller and has stronger robustness and anti-disturbance ability.

Guo, et al. [38] extended a study of the ADRC scheme by including a fault-tolerant control for attitude angle stabilization control of a quadrotor in the presence of wind gusts and sensor noise. Then, they estimated the total perturbation by an improved ESO and compensated by nonlinear feedback control law. The performance of the proposed control scheme was then compared to a PID based controller. The simulation result shows that ADRC can achieve accurate attitude control and stabilization without overshoot. It can compensate for the perturbation when the wind gust is introduced compared to PID based controller.

Ding, et al. [39] presented a linear ESO version of the ADRC scheme for altitude and attitude control of the quadrotor under wind gust, to act as a compensator that can effectively eliminate the wind gust. The optimization technique based on the ABC algorithm was used to get the optimal control performance. The simulation result shows that the attitude angle can be stabilized in a short time with high accuracy with ≈ 0 overshoot and less than 2% steady-state error. The quadrotor can reach the desired altitude faster and lesser steady-state error than the PID controller when the disturbance was introduced.

Model Predictive Controller (MPC). Model Predictive Controller (MPC) is used to control the process while satisfying the set of constraints. The controller relies on the linearize dynamic models that are often obtained by using a system identification process. It can predict the future behavior in the dependent variables of the system models that cause changes in the independent variables and take control action accordingly for optimizing the cost function. The MPC is classified as an advanced control method used to maintain the output at the operational and set points.

Chen, et al. [40] presented a cascaded linear MPC (LMPC) for the position and attitude control of the quadrotor. The advantage of the cascaded technique is that the desired attitude angle and thrust can directly be limited within an acceptable range. The Cascaded linear MPC gives a satisfactory performance and can follow the desired position and maintain the attitude angle close to the operating point without violating motor speeds.

Ganga, et al. [41] performed a comparative study between the conventional PID controller with LMPC for controlling the altitude motion of the quadrotor. The simulation shows that LMPC gives better control characteristics compare to PID with satisfied input constraints. It has a better settling time and no overshoot. Islam, et al. [42] conducted a study of LMPC under disturbance and model parameter uncertainties for trajectory tracking control of the quadrotor. The simulation result shows that LMPC can reject disturbance without affecting the controller output. It successfully tracks the desired trajectory under different disturbances with minimal RMSE, which is less than 5% in all X/Y/Z state.

In another work by Islam, et al. [43], a quaternion orientation based quadrotor system controlled by the MPC technique was presented for the trajectory tracking control. They used the quaternion approach to tackle the limitation poses by the Euler angle known as the singularity problem. A new cost function was developed to compensate for the quaternion approach since it is different from the attitude error of the Euler angle. The proposed controller based on RMSE on three different trajectories can maintain the control for all three trajectories. The quadrotor successfully tracks the desired path with a satisfactory tracking error. The RMSE in X/Y/Z state for both with and without disturbance is less than 5%. However, some delay occurs in the controller response due to the air drag.

Khan, et al. [44] presented a nonlinear MPC (NMPC) for controlling the altitude and attitude of the quadrotor. A discrete nonlinear model was used in which the parameter of the model was obtained from the input-output data taken from the PID control simulation and recursive least squares algorithm. The simulation result shows that the NMPC gives a good performance in tracking the desired path while maintaining the upper and lower limit of the control signal. The NMPC provides a good control performance and provides acceptable robustness against noise with slight oscillation.

Ru, et al. [45] presented a study of trajectory tracking control of the quadrotor using an NMPC method. The equivalent NMPC was designed by exploiting the state-dependent coefficient form used to model the system nonlinearities into the pseudo-linear system matrix. A comparative study with LMPC was made to realize the performance of the proposed controller. The simulation result shows that both controllers can provide a good tracking performance, but the transient response of the NMPC is better. The speed of tracking error and the desired path is much better for the NMPC. The NMPC also outperformed the linear MPC under the presence of disturbance.

Merabti, et al. [46] proposed a PSO algorithm based on NMPC for trajectory tracking control of the quadrotor in the presence of environmental perturbation. The purpose of the PSO was to solve the optimization problem of the NMPC. The finding shows that good tracking performance was obtained when there is no disturbance with an acceptable control limit. However, when the disturbance is present, the quadrotor moves away from the desired trajectory but later returns to the desired path again when the disturbance disappears.

4. INTELLIGENT CONTROL

Intelligent control is a control method that uses artificial intelligence computing approaches such as Neural Network, Fuzzy Logic, GA, etc. In dealing with a complex system, some traditional controllers still unable to give satisfactory performance to ensure the robustness of the system against parameter uncertainties and external disturbance. The capability of intelligent control methods in controlling such a system is why it is used because basic control methods face difficulty in controlling a complex system. Some of the most widely used intelligent controllers in quadrotor applications, namely Fuzzy Logic and Neural Network, are discussed.

Fuzzy Logic Controller. The Fuzzy Logic controller has been widely used and successfully implemented in the quadrotor application. The concept of the Fuzzy Logic is that the logic involved cannot be expressed as true or false instead as partially true where the value may be ranging between completely true and false. The advantage of Fuzzy Logic over another intelligent approach, such as Neural Network, is that the human operator can understand the solution to the problem. Raza, et al. [47] presented a Fuzzy Logic controller for controlling the position and attitude angle of the quadrotor under disturbance condition. Here, the Fuzzy Logic controller was implemented using two types of an inference engine, namely the Mamdani and Takagi-Sugeno-Kang fuzzy (TSK) model. Then a comparative study between those two inference models was done to evaluate the performance of the controller. Three simulation tests were conducted: 1) without disturbance, 2) the controller subjected to sensor noise, and 3) the controller subjected to a sensor noise and a medium wind gust of 10 m/s. The finding shows that the Fuzzy Logic controller with both inference engines gives satisfactory performance even in sensor noise and wind disturbance. However, the Fuzzy Logic controller based on the Mamdani inference engine gives faster response time than the TSK model with significant drift in yaw angle under disturbance.

Zare, et al. [48] conducted a study of trajectory tracking control of the quadrotor using the Fuzzy Logic controller based on the Takagi-Sugeno-Kang (TSK) inference engine. The simulation result shows that the Fuzzy Logic controller provides good performance in tracking and controlling the desired position and orientation angle of the quadrotor. Yazid, et al. [49] proposed a position controller of the quadrotor using first-order Takagi-Sugeno-Kang (TSK)

Fuzzy Logic controller based on an optimization algorithm. In their study, three evolutionary algorithms, namely GA, PSO, and ABC were used to facilitate automatic tune of the previous and subsequent parameter of the controller. Then the performance of the proposed controller was compared under three different flight conditions: constant step input, varying step input, and the sine function. The finding shows that for a given constant step input, the controller can stabilize the quadrotor and can track the desired reference successfully within a short time.

Neural Network Controller. Neural networks have attracted much attention from the researchers nowadays due to their ability to deal with complex and computationally demanding tasks. The concept of Neural Network is based on a collection of connected artificial neurons in a biological brain. Each connection transmits a signal to other neurons, then processes the signal and signals another neuron connected to it. The Neural Network controller has been successfully used to design a system with nonlinear dynamics and system errors. Boudjedir, et al. [50] proposed an adaptive Neural Network controller based on Neural State Observer (NSO) for the trajectory tracking of the quadrotor. The purpose of an adaptive technique was to solve the uncertainties of the dynamic system of the controller. A Single Hidden Layer Neural Network was used, and the state observer was designed based on a sliding mode observer structure. The Lyapunov direct method has been used to prove the global system stability. A comparative study between the proposed observer with the sliding mode observer was done. The simulation result shows that a very noisy signal in roll and pitch angle is produced by SMO, while the proposed observer can minimize the measurement noise in all attitude angles. It also can track the desired attitude angle well compared to SMO. Overall, the proposed observer shows a significant reduction in measurement noise without any performance degradation. Xiang, et al. [51] presented an adaptive nonlinear controller based on Dynamic Inversion and Neural Network for the trajectory tracking control of the quadrotor in the presence of uncertainties and actuator dynamics. The Neural Network was used to eliminate the inversion error due to disturbance, and parameter uncertainties of the Dynamic Inversion controller. The performance of the proposed controller was compared with the conventional Dynamic Inversion controller and PID controller. The finding shows that the PID controller shows poor performance in the presence of uncertainty and disturbance. Dynamic Inversion controller performs much better than PID in the presence of disturbance and noise. Neural Network-based Dynamic Inversion controller shows the effectiveness in eliminating the model inversion error and improving the performance of the system.

Muliadi, et al. [52] conducted a comparative study between the Artificial Neural Network-based Direct Inverse Control (DIC-ANN) and the conventional PID controller for altitude and attitude control of the quadrotor. The controller allows the Neural Network to directly control the dynamics of the system and achieve the desired response. The simulation shows that a remarkable tracking accuracy showed by DIC-ANN. PID in following the take-off flight profile. The PID produces a lower error in terms of following the reference but experiences oscillation until the ramp is ended. Nevertheless, the DIC-ANN provides better performance than the PID controller in controlling the altitude and attitude angle of the quadrotor.

5. SUMMARY

A detailed comparison of all discussed controller design techniques is tabulated in Table 1 for a brief view and understanding in selecting the appropriate controller design technique for future research. This table presents a summary of existing quadrotor controller design techniques based on their application and mode of analysis (i.e., simulation, experimental, or both) done by various researchers in developing their controllers.

Table 1 – Summary of Existing Quadcopter Controllers and its Application

Author	**Controller Technique**	**Method**	**Application**
Li, et al. [3]	PID	Simulation & experimental	Position & Attitude
Praveen, et al. [53]	PID	Simulation & experimental	Attitude
Castillo-Zamora, et al. [4]	PID	Simulation	Position & Attitude
Pan, et al. [5]	PID with KF	Simulation	Trajectory Tracking
Joyo, et al. [54]	PID with EKF	Simulation	Position
Tanveer, et al. [55]	PID with EKF	Simulation	Altitude & Attitude
Imane, et al. [6]	RM based PID	Simulation	Altitude & Attitude
Imane, et al. [6]	GA based PID	Simulation	Altitude & Attitude
Alkamachi, et al. [56]	GA based PID	Simulation	Trajectory Tracking
Adriansyah, et al. [57]	PSO based PID	Simulation	Attitude
Erkol [7]	ABC/PSO/GA based PID	Simulation	Altitude & Attitude
El Gmili, et al. [58] Nada El, et al. [59]	PSO/CS/PSO-CS/RM based PID	Simulation & experimental	Trajectory Tracking
Hasseni, et al. [60]	GA/ES/DE/CS based PID	Simulation	Trajectory Tracking
Ahmad, et al. [8]	PD/PID	Simulation	Altitude & Attitude
Hong, et al. [61]	Gain Scheduling based PD	Simulation & experimental	Trajectory Tracking
Subudhi, et al. [62]	Cascaded PD-PD	Simulation	Trajectory Tracking
Burggräf, et al. [9]	Cascaded P-PID	Simulation & experimental	Attitude
Abdelhay, et al. [63]	Cascaded PD-PID	Simulation	Trajectory Tracking
Moreno-Valenzuela, et al. [64]	NPID	Experimental	Trajectory Tracking
Medjdoubi, et al. [10]	NPID	Simulation	Altitude & Attitude
Najm, et al. [65]	GA based NPID	Simulation	Position & Attitude
Hernandez-Martinez, et al. [12]	LQR	Simulation	Trajectory Tracking
Okyere, et al. [13]	LQR	Simulation	Altitude
Zhi, et al. [14]	LQR with KF	Simulation	Attitude
Kurak, et al. [66]	LQR with KF	Simulation	Attitude
Martins, et al. [15]	Integral LQR with KF	Simulation & experimental	Trajectory Tracking
Shah, et al. [16]	Gain scheduling based Integral LQR	Simulation	Trajectory Tracking
Falkenberg, et al. [17]	H∞	Simulation & experimental	Attitude
Rich, et al. [18]	H∞	Simulation & experimental	Altitude & Attitude
Alkamachi, et al. [19]	H∞	Simulation	Position & Attitude
Noormohammadi-Asl, et al. [20]	H∞	Simulation & experimental	Attitude
Bonna, et al. [21]	Feedback Linearization	Simulation	Trajectory Tracking
Chalidia, et al. [22]	Feedback Linearization	Simulation	Attitude
Ye [23]	Feedback Linearization	Simulation	Trajectory Tracking
Joukhadar, et al. [67]	Feedback Linearization	Simulation & experimental	Trajectory Tracking
Huo, et al. [24]	Backstepping	Simulation	Attitude
Tripathi, et al. [25]	Backstepping	Simulation	Position & Attitude
Basri, et al. [26]	PSO based Backstepping	Simulation	Altitude & Attitude
Lu, et al. [27]	Online optimization-based Backstepping	Simulation & experimental	Trajectory Planning & Tracking
Nguyen, et al. [29]	Adaptive Backstepping	Simulation	Trajectory Tracking
Saud, et al. [28]	PSO based Integral Backstepping	Simulation	Trajectory Tracking
Zheng, et al. [68]	Adaptive Integral Backstepping	Simulation & experimental	Position & Attitude
Cömert, et al. [30]	SMC	Simulation	Altitude & Attitude
Rashdi, et al. [69]	SMC	Simulation	Altitude & Attitude
Zheng, et al. [31]	Second-Order SMC	Simulation	Trajectory Tracking
Elhennawy, et al. [70]	Second-Order SMC	Simulation & experimental	Position & Attitude
Xiong, et al. [71]	Discrete-time SMC	Simulation	Position & Attitude
Nadda, et al. [72]	Adaptive SMC	Simulation	Altitude & Attitude
Mofid, et al. [32]	Adaptive SMC	Simulation	Altitude & Attitude

Xiong, et al. [73]	Robust Terminal SMC	Simulation	Position & Attitude
Xiu, et al. [74]	Improved Global SMC	Simulation	Position & Attitude
Dou, et al. [75]	Adaptive SMC	Simulation	Attitude
Mohammadi, et al. [33]	MRAC	Simulation & experimental	Altitude & Attitude
Ghaffar, et al. [34]	MRAC	Simulation & experimental	Altitude
Xu, et al. [35]	L1 Adaptive Control	Simulation	Fault-tolerant
Thu, et al. [76]	L1 Adaptive Control	Experimental	Position & Altitude
Dou, et al. [36]	ADRC	Simulation	Altitude & Attitude
Zhang, et al. [37]	ADRC	Simulation	Trajectory Tracking
Guo, et al. [38]	ADRC with Improved ESO	Simulation	Fault-tolerant
Ding, et al. [39]	Linear ADRC	Simulation	Altitude & Attitude
Chen, et al. [40]	LMPC	Simulation	Position & Attitude
Ganga, et al. [41]	LMPC	Simulation	Altitude
Islam, et al. [42]	LMPC	Simulation	Trajectory Tracking
Islam, et al. [43]	LMPC	Simulation	Trajectory Tracking
M, et al. [77]	LMPC with EKF	Simulation	Altitude & Trajectory Tracking
Khan, et al. [44]	NMPC	Simulation	Altitude & Attitude
Ru, et al. [45]	NMPC	Simulation	Trajectory Tracking
Zanelli, et al. [78]	NMPC	Simulation & experimental	Attitude
Merabti, et al. [46]	PSO based NMPC	Simulation	Trajectory Tracking
Wang, et al. [79]	Constrains based NMPC	Simulation	Trajectory Tracking
Raza, et al. [47]	Fuzzy Logic (Mamdani)	Simulation & experimental	Position & Attitude
Zare, et al. [48]	Fuzzy Logic (TSK)	Simulation	Trajectory Tracking
Talha, et al. [80]	Fuzzy Logic	Simulation & experimental	Auto Landing
Yazid, et al. [49]	GA, PSO, ABC based Fuzzy Logic	Experimental	Position
Boudjedir, et al. [50]	Neural -based Adaptive ANN	Simulation	Trajectory Tracking
Xiang, et al. [51]	NN based Adaptive Dynamic Inversion	Simulation	Trajectory Tracking
Muliadi, et al. [52]	NN based Direct Inverse Control	Simulation	Altitude & Attitude
Doukhi, et al. [81]	Adaptive Certainty Controller-NN	Simulation	Trajectory Tracking
Jiang, et al. [82]	DI-Sigma-Pi Neural Network	Simulation & experimental	Trajectory Tracking

It shows that out of 80 controller design techniques used, 72.5% of the researchers conducted a simulation study, and about only 3.75% performed experimental studies on a real quadrotor platform. In contrast, 23.75% of the researchers performed both simulation and experimental studies to validate the simulation results. In some cases, they found that the simulation outcome sometimes completely differs from the experimental result due to either simplification made to the quadrotor dynamics or an unexpected external disturbance present in the real application that is not being accounted in the simulation process. The performance of the controller was perceived differently throughout this survey, depending on the techniques used. It shows that the controller with an optimization technique for automatically tuning the optimal controller gain parameters gives a good performance than the traditional controller with a manual tuning method. Furthermore, the nonlinear and intelligent controller provides a better coping strategy in dealing with the complex nonlinearity of the quadrotor dynamics. The superiority and downside of each of the controllers are presented in Table 2.

Table 2 – Advantages and disadvantages of Existing Quadcopter related Controllers

Control Technique	**Advantages**	**Disadvantages**
PID Control	Practical and easy to implement, not dependent on the mathematical model	Can be unstable if not tuned properly, not optimal a problem
LQR Control	A simple method provides optimal solutions	Less robust, cannot handle nonlinearities in the system
H∞ Control	Does not require an accurate model, high robustness	High complexity, difficult to adjust the parameter

Feedback Linearization Control	Flexible control design, a smooth control signal	Can't handle external disturbance, a mathematical model required
Backstepping Control	Able to handle external uncertainties well, efficient for the under actuated system	Lack of robustness, large control signal's magnitude, strictly feedback form
Sliding Mode Control	Robust against model uncertainties, simple structure, easy to tune	Chattering effect, a discontinuous control law
Adaptive Control	Wide operation range, good unknown parameter handling, no model needed	Limited flexibility, complex adaptation law, lack robustness
Active Disturbance Rejection Control	Good robustness, simple structure, can handle parameter uncertainties	Difficult to adjust the parameter
Model Predictive Control	Cost-effective and can predict the future behavior of the system, good robustness	Depends on system knowledge, high computational consumption
Fuzzy Logic Control	Based on the linguistic model, no model required, improved control performance	Intensive simulation needs to be trained, design complexity
Artificial Neural Network Control	No model required, improved control performance, great model prediction	Intensive simulation needs to be train, design complexity

In general, a PID controller provides a practical solution for the control strategies with easy implementation on the real system and does not depend on the mathematical model of the quadrotor. However, the controller gain must be properly tuned to achieve a stable system. An optimal controller such LQR is a simple control method that provides an optimal solution for the control problem. Still, it cannot handle the system's nonlinearity presented in the quadrotor. Thus the system must be linearized first to use this type of controller, and it also lacks robustness.

The $H\infty$ controller gives high robustness for the system where it can manage to deal with external disturbance and parametric uncertainty that arise in the system dynamics. It can be designed even if the full knowledge of the system is unknown. For such a control system, the controller parameters are difficult to adjust and the system also has a higher complexity. FL can deliver a smooth control signal with a flexible controller design. Yet, it required an exact mathematical model of the system, and it cannot be handled properly concerning the external disturbances.

On the other hand, the Backstepping controller is known for handling well an external uncertainty and it is said to be an efficient controller for the under actuated system. However, still, it lacks robustness, has large control signal magnitude, and strictly feedback form. The Sliding Mode Control can come up with robustness against the model uncertainties, has a simple structure, and the controller parameters are easy to tune. However, its real implementation is not desired since it used a discontinuous control law that caused a chattering effect. An adaptive controller can provide a good performance since it can adapt to unknown parameters in the system while it does not require to know the model of the system. Still, it needs to deal with a complex adaptation law and a lack of system robustness. ADRC can provide a robust performance of the system with the ability to handle a parameter uncertainty. It also does not need an accurate mathematical model of the system. Thus, this method gives a better solution if the full knowledge of the system is not available, but it is facing the difficulty to adjust the controller parameters.

A Model Predictive Control is one of the cost-effective controllers that can predict the future behavior of the system and can ensure the system robustness. Still, it depends on the full knowledge of the system and also has to deal with high computational consumption. Fuzzy Logic and Neural Network controller do not require a model to be designed, yet they improve the performance of the control system. The difference between these two controllers is that the Fuzzy Logic controller can provide a solution to the problem that can be understood by the human operator since it is based on a linguistic model.

Regardless, an intensive simulation is needed to be trained, and design complexity is arising when designing these types of controllers. Overall, the performance of the controllers greatly depends on various criteria, such as the controller parameters and the specification of the quadrotor used. For example, although the same type of controller is used for controlling the quadrotor, different controller gain is required to achieve good performance. Similarly, in the dynamic model of the quadrotor, different specifications, such as the mass and inertia, produce different performances. Therefore, each controller design technique has its features and advantages that depend on how the design requirement outlined its priority.

6. CONCLUSIONS

A comprehensive survey on various controller design techniques commonly used for stabilizing and controlling the rotational and translational states of the quadrotor has been presented. Three different categories, namely the linear, nonlinear, and intelligent controllers with their respective controller designs under those categories have been discussed based on their performance specifications in terms of the rise time, settling time, overshoot, and steady-state error of the system. Comparative studies of different controller models were summarized to highlight their performances. The advantages and disadvantages of the controllers were also presented. Studies have shown that even a slight alteration to the existing controller design can improve the performance of the system.

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