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A Comprehensive Review and Applications of Active Disturbance Rejection Control for Unmanned Aerial Vehicles

SOFIANE KHADRAOUI[1], RAOUF FAREH[1], MOHAMMED BAZIYAD[2], MAHMOUD BAKR ELBELTAGY[3], and MAAMAR BETTAYEB[1]

[1]Department of Electrical Engineering, University of Sharjah, 27272, Sharjah, UAE (e-mail: skhadraoui@sharjah.ac.ae; rfareh@sharjah.ac.ae; maamar@sharjah.ac.ae)
[2]Research Institute of Sciences & Engineering (RISE), University of Sharjah, 27272, Sharjah, UAE (e-mail: mbaziyad@sharjah.ac.ae)
[3]School of Engineering at the University of British Columbia, Okanagan campus, 1137 Alumni Ave Kelowna, BC V1V 1V7 Canada (e-mail: melbelta@mail.ubc.ca)

Corresponding author: Sofiane Khadraoui (e-mail: skhadraoui@sharjah.ac.ae).

ABSTRACT Over the past few decades, there has been a consistent interest in the creation and use of Unmanned Aerial Vehicles (UAVs). Although originally developed for military purposes, such as surveillance and target acquisition, UAVs are now being utilized in a variety of fields, including tourism, public safety, transportation, and healthcare. Due to the considerable interest in the use of UAVs and their complex dynamic behavior, there has been a growth in the design and practical implementation of different control methods to accomplish their tasks and missions successfully. Control approaches developed for UAV systems mainly include adaptive control, robust control, and Active Disturbance Rejection Control (ADRC). Recently, ADRC has gained significant popularity as a control method for UAVs due to its robustness against uncertainties and disturbances, as well as its ease of implementation. This review paper aims to provide a comprehensive evaluation and insightful look into the various ADRC structures developed for UAV systems, as well as to highlight the basic issues involved in this field. This will allow readers to identify potential future requirements for expanding the utility of UAVs. An illustrative example of the ADRC scheme in the Parrot Mambo quadcopter is also included in this review paper.

INDEX TERMS ADRC, Tracking control, Rotary UAVs, Fixed-wing UAVs, Hybrid UAVs, Quadcopters

I. INTRODUCTION

WITH the recent and rapid advancement in science and technology, Unmanned Aerial Vehicles (UAVs) have become widely utilized to provide optimized services and accomplish sophisticated tasks. In the past, UAVs were mainly developed for military purposes. Nowadays, UAVs are not only present in the military sector but are also extensively employed in diverse applications and vital fields such as public safety, transportation, and healthcare. This is due to several attractive advantages, such as application adaptivity and movement flexibility. The importance of integrating UAVs is most readily apparent in cases where manned flights become dangerous or difficult. Therefore, several reports have witnessed the successful integration of UAVs in many critical and challenging applications, including firefighting, search and rescue, or inspection of power lines and pipelines [1].

The complex structures of UAVs, along with their complex nature of tasks and specific applications, have revealed a serious issue for scientists in achieving the intended goals and objectives. Control design strategies for UAVs are of great importance for effectively fulfilling the assigned UAV tasks. Scientists and researchers face several challenges when developing trajectory control systems for UAVs. The first challenge is mainly related to the complexity of the mechanical structures and the behavior of UAV systems. Most of the system complexity is generally caused by the propeller rotation and the blade flapping of the UAV [2], as well as the inherent nonlinearities and strong coupling of the position and orientation dynamics [3]. Besides, UAV systems are Multi-Input Multi-Output (MIMO) underactuated mechanical systems with a fewer number of actuators than the number of degrees of freedom [3]. Moreover, UAV systems generally exhibit multiple-input time delays in their dynamic behavior and involve time-varying states, which increase the complexity of UAV systems. In addition, UAV systems are subject to parametric uncertainties and different disturbances, including aerodynamic forces and moments such as air resistance and sudden wind gust. It is well known that all the aforementioned characteristics of UAV systems may significantly affect the desired stability and performance specifications. Therefore, the development of advanced control design schemes has become, over the past few years, a priority research topic to overcome the challenges of UAV systems and successfully control them [4]–[7].

Classical control strategies, such as PID control, have been adopted in several aerial applications [8], [9]. However, due to the fact that the UAV dynamic behavior is complex and subject to non-negligible uncertainties and disturbances as outlined above, modern control strategies are needed to ensure the performance of the tracking system, especially when operating in unstable environments [10]. Generally, two modern control approaches, namely adaptive control and robust control, have been studied to efficiently control different UAV systems [11]–[16]. On one hand, adaptive controllers are developed to control plants with uncertainties and have the ability to adjust the parameters online according to the current operating conditions and environment. The design of adaptive controllers relies on a mathematical model that accurately describes the dynamics of the UAV system. On the other hand, robust control methods that are capable of accounting for uncertainties and disturbances have been developed for UAVs. In robust control theory, the uncertainties are explicitly addressed by determining a bounding set that should contain the disturbances and the system parameters. Generally, robust controllers allow us to achieve acceptable performance for a bounded set of UAV uncertainties and disturbances. Therefore, robust controllers are safe to be static, and they do not need to adaptively modify the controller parameters and gains, which would reduce the complexity of the control design. The goal of applying the abovementioned modern control methods to UAV systems was to practically reduce the effect of disturbances and achieve the desired performance specifications. However, despite the considerable advancements made in such control theories, which have shown acceptable tracking performance in UAV applications, the control of a complex MIMO UAV system is still a challenging task, especially with the variety of disturbances and the highly nonlinear as well as variable behavior of UAV systems. The design of a robust controller needs a predefined set where the uncertainties and disturbances should reside in. However, considering the fact that UAV systems are often operated in different variable environments, they are subject to a wide range of uncertainties and disturbances that could easily reside outside the determined boundary set. However, the main limitation of adaptive controllers is that their design relies on accurate prior information on the UAV system dynamics to tune the controller's parameters. Given the challenges outlined above, the application of adaptive and robust control techniques to UAV systems becomes impractical because UAV systems are designed to operate across diverse environments that have different characteristics and that involve unknown or variable payloads. Hence, to account for the large unknown but possibly unmeasurable disturbances and uncertainties, the use of observers-based control approaches is a possible solution to tackle the control problem of UAV systems. The basic idea of the observer-based control schemes is to implement an observer to estimate the disturbances acting on the plant during operation and feedback on the estimated signals to build a robust control law with disturbance rejection capabilities in real-time. Observer-based control systems have shown some success in treating the effect of unknown disturbances in several applications. However, the observer design requires the availability of an accurate plant model, but some critical issues still arise when practically implementing observer-based controllers. Moreover, the performance of these controllers is highly related to the reliability of the disturbance estimator, which is strongly dependent on the complexity of the plant. In addition, the observer-based control design philosophy has not been widely adopted by the control community of UAVs due to the limited availability of appropriate analysis and synthesis tools. All of the previously-discussed issues caused serious challenges to successfully and adequately control UAV systems, especially with the continuously increasing complexity of recent applications. Therefore, there is a need to find a more appropriate, practical, and simple control strategy that can successfully handle the complex characteristics of UAV systems as well as the impact of various unmeasurable disturbances and uncertainties.

In the 1990s, a novel control method, namely the Active Disturbance Rejection Control (ADRC), was proposed by Jingqing Han to solve the problems mentioned above [17], [18]. Thus, the ADRC control method has been commonly adopted in various applications, such as robotics and aviation. The principle of the ADRC approach is based on the idea of introducing a fictitious state that includes all possible uncertainties and disturbances originating from the plant (called total disturbance) that are unknown and not accounted for the plant model. The total disturbance in an ADRC scheme is estimated in real-time using an Extended State Observer (ESO), and then the estimation is utilized to build a suitable control law capable of decoupling the system from all unknown uncertainties and disturbances affecting the system dynamics. The main features of the ADRC method are related to several aspects: 1) it is unique in its conceptualization and characterized by ease of implementation in real-world contexts; 2) disturbances are rejected in real-time; 3) the control design process does not necessitate detailed knowledge of system dynamics; and 4) it is applicable to nonlinear complex MIMO systems, including sophisticated UAV systems. All these remarkable advantages of the ADRC control strategy have attracted many control practitioners to adopt it in a wide range of applications. The first practical utilization of ADRC controllers was in 2010 at Parker Hannifin Extrusion Plant

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in the United States [19]. The ADRC implementation had successfully enhanced productivity by 30% and contributed to the reduction of the required operation energy by 50%. In addition, ADRC algorithm was implemented at the National Superconducting Cyclotron Lab in the United States as an energy particle accelerator [20]. Moreover, the well-known semiconductor production company, Texas Instruments, has invented ADRC-based motion control chips in 2013 [21]. These successful experiences have enabled the ADRC control method to be a good candidate for the substitution of the Proportional Integral Derivate (PID) utilized in several industrial systems due to its simple design structure and strong ability to deal efficiently with uncertainties and disturbances. The ADRC technique was already proven to be a promising solution in robotics applications [22], [23].

As far as the authors are aware, although the ADRC control method has been widely used to control UAV systems in the last few years, the literature shows the lack of a research review that highlights the existing works dealing with the implementation of ADRC to control UAV systems. To identify this gap, we conducted a comprehensive literature search to review recent and old relevant articles, conference papers, and reports published over the past several years. Our focus was on studies that implemented ADRC techniques in UAV applications to analyze their findings and contributions and evaluate the coverage of existing research. This search process helped us conclude that although ADRC has been successfully applied in many fields, there is still a significant lack of comprehensive reviews specifically addressing its application in UAV systems. From a practical point of view, UAV systems are one of the most uncertain systems that are subject to various complex/varying disturbances and work in different conditions and environments. These disturbances mainly include weather conditions such as vertical wind gusts and air turbulence induced by the propellers at near-earth flights such as land and take-off, which greatly affect the dynamic behaviors and the stability of the UAV systems. For this reason, there is a persistent need for a suitable control approach to deal with these challenges. The ADRC technique is considered a good candidate to deal with such systems due to its capability of rejecting complex disturbances and ensuring good dynamic behavior. Therefore, this article provides a thorough research review on the application of the active disturbance rejection control method and its variants to solve serious UAV control problems, such as attitude control, obstacle avoidance, takeoff and landing, stability, and trajectory control. The main objective of this review paper is to present state-of-the-art on the design and implementation of various ADRC structures to UAV systems. In addition, we aim to draw the robotics and control community's attention to explore different research directions related to the use of the ADRC approach in UAV systems motivated by the research gaps in this important application area.

The rest of this paper is organized as follows: Section II presents the classification and applications of UAV systems. The theoretical foundation of the ADRC control method is presented in Section III. Section IV discusses the applications of various ADRC structures to different classes of UAVs. An application of the ADRC technique to control a quadcopter is given in Section V. Finally, the conclusion is given in Section VI.

II. CLASSIFICATION AND APPLICATION

To help distinguish the existing UAVs based on their characteristics and their potential applications, we aim in this section to highlight the main categories of UAV systems. Different UAV classification schemes have been adopted in the literature [24]. UAVs are mainly categorized into three main classes: rotary, fixed-wing, and hybrid UAVs [25], [26]. Although rotary UAVs have received considerable attention and interest, fixed-wing UAVs and hybrid UAVs found their application in various fields. Each of these types of UAV has its own advantages and disadvantages, including their appropriateness for certain applications. The classification used in this paper is summarized in Figure 1.

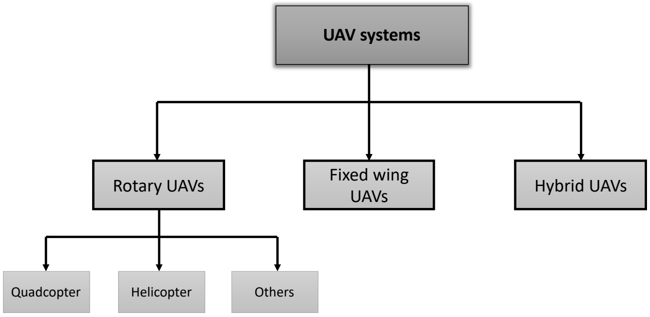

FIGURE 1. Classification of UAVs

A. ROTARY UAVS

Rotary UAVs are based on the lift generated by the continuous rotation of rotor blades which provides the rotary UAVs with the ability to hover and move in any direction. This category is classified into multirotor UAVs and single-rotor UAVs. Multirotor UAVs include tri-copters (3 rotors), quadcopters (4 rotors), hexacopters (6 rotors), and octocopters (8 rotors), among others. The main advantages of this multirotor category are their stability, flexible control, and maneuverability, as well as their ability to hover, take off, and land vertically [26], [27]. Therefore, they do not need a large area for take-off and landing. However, they often have a limited flying time and small payload capabilities. Multirotor UAVs are generally used in many applications, such as aerial photography, videos, site inspection, and construction. Conversely, rotary UAVs such as helicopters have one single big rotor, which makes them strong, durable, and capable of flying for a long time and carrying a heavy payload. Nevertheless, single-rotor UAVs are harder to fly than multi-rotors and can be dangerous due to the heavy spinning blade.

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B. FIXED-WING UAVS

Fixed-wing UAVs have static wings and look like traditional and conventional airplanes. They are designed to fly in high altitudes and to cover large areas with a single battery. Moreover, fixed-wing UAVs have high flight speeds with long endurance in addition to their ability to carry more weight than the rotary UAVs [26], [27]. In case of power loss, they are able to continue flying and landing safely. However, they have some disadvantages, such as the need for long distances to take off and land, less maneuverability than rotary UAVs, and larger airframes. In addition, unlike the rotary UAVs, they cannot hover, and they do not have a take-off ability. The flying time ranges, as well as the speed, make this category ideal for military, agriculture, and surveillance applications.

C. HYBRID UAVS

Recognizing that rotary and fixed-wing UAVs have their disadvantages and limitations, some manufacturers have produced hybrid UAVs to benefit from the advantages of both categories. The Hybrid UAVs include both rotors and wings at the same time. They can take off and land like rotary UAVs and are able to fly like fixed-wing UAVs. Hybrid UAVs are mainly designed to profit from both advantages of the previous two categories: high range and endurance flights with VTOL ability. However, due to the hybrid configuration, their mechanical and aerodynamic structure is relatively complex. Therefore, the maintenance costs are high compared to other UAV categories. This versatility in the structures of the hybrid UAVs makes them a good candidate for delivery purposes. Table 1 presents the main advantages and disadvantages of the most common types of UAVs and their applications. Figure 2 illustrates an example of a hybrid UAV [28] featuring a quadcopter (Motor M1 to M4) and a fixed-wing that has pusher propeller M5; left and right aileron control servos (servo 1 and 2) and elevator and rudder control servos (Servo 3 and 5).

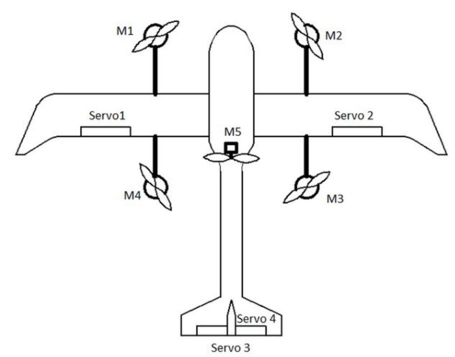

FIGURE 2. Hybrid UAV [28]

III. FUNDAMENTALS OF ADRC

The basic idea and the topology of the ADRC technique are presented in this section to illustrate the main components and the mathematical development behind the ADRC approach. The classical Proportional-Integral-derivative (PID) controller is considered by far one of the most popular and successfully utilized controllers in engineering systems and industry. It is recognized that the PID controller does have a certain degree of robustness (based on the tuning of its gains) to small plant uncertainties. Nevertheless, when faced with large-scale plant uncertainties and disturbances, the PID controller may cause a deterioration of the required system performance due to the fact that it does not have the ability to readjust its parameters online. The ADRC technique, which inherits the advantages of PID controllers in terms of simplicity and ease of implementation, seems to be an appealing solution to address this control problem that is frequently encountered in many practical applications. This is mainly due to its valuable characteristics, such as the capability of estimating and compensating for a diverse range of uncertainties and disturbances in real-time, in addition to ensuring a good transient response. The ADRC architecture primarily comprises a Tracking Differentiator (TD), an Extended State Observer (ESO), and a feedback controller as shown in Figure 3. The tracking differentiator defines the desired transient process and provides the system reference input, while the ESO allows the estimation of unknown uncertainties and disturbances affecting the system. The feedback controller is utilized to provide a desired transient control performance by actively rejecting the disturbance estimated while tracking the system input references. In Figure 3, u is the suitable control law that eventually steers the system output $y(t)$ to closely track the desired input trajectory $r(t)$.

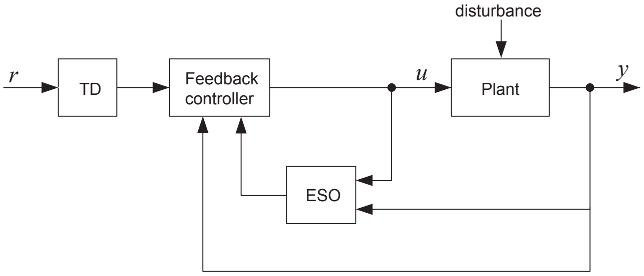

FIGURE 3. Topology of active disturbance rejection control

In this section, we aim to briefly illustrate the idea of the ADRC technique for a n^{th} order nonlinear system defined by the following n^{th} state space model:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 \\ \quad \vdots \\ \dot{x}_n = f\left(t, x_1, \ldots, x_{n-1}, \nu\right) + bu \end{cases} \tag{1}$$

where b is the input gain (called also high-frequency gain) and $x_i(t)$ (for $i = 1, \ldots, n$) denote the system states. $f(.)$ denotes a disturbance function. It should be mentioned that the exact value of the input gain b is generally unknown,

TABLE 1. **Advantages/disadvantages of UAV systems and their applications**

UAV Type	Advantages	Disadvantages	Applications
Rotary	• Multi-directional • Stability • Easy to control	• Short flight times • Limited payload • Small area coverage	• Photography and Video • Site inspection • Emergency
Fixed wing	• Long endurance • Large range • High speed	• Large space required to launch & recovery • No hovering • Low maneuverability	• Military • Agriculture • Power line inspection
Hybrid	• VTOL capability • Long endurance	• Not perfect for hovering or forward flight • In development	Delivery

which makes the selection of a suitable value for the high-frequency parameter b a major difficulty. However, an estimate of it can be used to simplify the control design process. An approximated value of b can be obtained empirically via conducting an experiment or derived from the system's mathematical model. Although the uncertainty in the high-frequency parameter b can be treated as a component of the total disturbance, it can still lead to variations in the system output and may deteriorate the performance and stability of the system. Nevertheless, if the true value of the input gain b is unknown, the use of an approximated value of b, along with an appropriate selection of the observer and controller bandwidths, can generally lead to a satisfactory control of ADRC. Some studies [29]–[31] indicate that the choice of larger values for the input gain b is recommended to improve the system stability and enlarge the allowable observer bandwidth. Simulation experiments have shown that overestimating the value of the high-frequency gain b with higher observer bandwidth can lead to relatively aggressive control laws. These laws may exhibit high noise sensitivity, result in a faster response with overshoot, and reduce overall robustness. On the other hand, underestimating the value of the high-frequency gain b can result in better robustness against disturbances and low noise sensitivity, but yields a slower response. Moreover, underestimating b requires careful selection of an observer bandwidth from a narrow range of values to maintain closed-loop stability. Hence, a compromise is needed between achieving better performance and ensuring both stability and robustness to balance the selection of the input gain b and the observer bandwidth. The authors in [32] assumed that $\frac{b}{b_0} \in \left(0, 2 + \frac{2}{n}\right)$ to ensure the convergence and stability of ADRC, where b_0 is the approximated value of the exact high-frequency gain b and n is the relative order of the system. As a possible guideline for choosing the input gain if its exact value is unknown, one can start with a relatively large gain b to provide the designer with more flexibility in specifying the observer and controller bandwidths and ensure the stability of the closed-loop system. Once the bandwidths are specified, one can decrease the value of the gain b to achieve the desired closed-loop transient performance profile with tolerable noise sensitivity and maintain a high level of robustness.

The idea of ADRC relies on introducing an extra-state $x_{n+1} = f$ in the state equations (1) to obtain an augmented state-space representation, which is then utilized for the ESO design [17] to estimate the total disturbance f:

$$\begin{cases} \dot{\hat{x}}_1 = \hat{x}_2 - g_1(e_1) \\ \dot{\hat{x}}_3 = \hat{x}_3 - g_2(e_1) \\ \quad \vdots \\ \dot{\hat{x}}_n = \hat{x}_{n+1} - g_n(e_1) + bu(t) \\ \dot{\hat{x}}_{n+1} = -g_{n+1}(e_1) \end{cases} \tag{2}$$

where $e_1 = \hat{x}_1 - x_1$ is the estimation error, while $g_i(e_1)$ (such that $i = 1, \ldots, n+1$) represents a linear/nonlinear function of the estimation error e_1. The function $g_i(e_1)$ should be appropriately chosen so that the observer states, $\hat{x}_i$, converge very closely to the states x_i, including the total disturbance $x_{n+1} = f$. The ADRC method generally aims at actively estimating and rejecting the total disturbance along with achieving a satisfactory closed-loop transient profile. The ADRC law applied to the plant is generally expressed as [17]:

$$u = b^{-1}(-\hat{x}_{n+1} + u_0) \tag{3}$$

where u_0 is the signal provided by the feedback controller. A suitable structure of the feedback controller in ADRC should be selected to ensure closed-loop stability as well as the desired performance specifications.

The ADRC structure can generally be classified into linear ADRC and nonlinear ADRC depending on the type of the ESO and the feedback controller. Both, nonlinear and linear ADRC structures have been widely implemented in various real systems because of their own strong aspects and advantages. In the nonlinear ADRC strategy, which has been developed by Han [17], [18], the design of the ESO and the feedback controller is based on the use of nonlinear functions. The nonlinear functions of the main control law, as well as the state observer, are seen as the driving force to account for and compensate for different unknown uncertainties and disturbances. Considering the nonlinear and complex nature of the uncertainties and disturbances presented within many physical systems, the nonlinear ADRC structure is shown to be more suitable and effective in achieving a satisfactory closed-loop transient profile in spite of unknown uncertainties and disturbances. Nevertheless, the design process is relatively complex due to the large number of controller parameters as well as the difficulty of closed-loop stability analysis. To this end, the linear ADRC structure, which is attractive and simplified with respect to the control tuning parameters and theoretical assessment, is proposed by Gao [33]. As a result, the linear ADRC structure has been favored in several control systems proposed in prior studies due to its design simplicity and stability analysis.

A comparative study discussing the strengths and weaknesses of both linear and nonlinear ADRC approaches is presented in [34]. The comparison confirms the superiority of the nonlinear ADRC scheme over the linear ADRC due to its ability to accommodate dynamic uncertainties and disturbances. In addition, it has been reported that the nonlinear ADRC structures are less sensitive to initial state errors compared to the linear ADRC structure. Nonetheless, the research confirms that, in some cases, the linear ADRC controllers can indeed achieve better performance than the nonlinear ADRC scheme. In particular, it has been proved that the linear ADRC performs well if the magnitude or the rate of change of the disturbance is relatively high. In contrast, the performance of nonlinear active disturbance rejection control laws can significantly deteriorate. Hence, the choice between linear ADRC and nonlinear ADRC is largely determined by the control goals and the specific application. For the purpose of taking advantage of both ADRC frameworks (linear and nonlinear), a switching ADRC strategy has been presented in [35] and tested on a simple ball and beam setup.

IV. ADRC FOR UAV SYSTEMS

Based on the diversity in the types of UAVs discussed in Section 2, we aim in this section to present the state of the art of the adoption of the ADRC strategy in controlling each class of UAV systems as well as to highlight the related open problems.

A. ADRC FOR ROTARY UAVS

Rotary UAVs are the most commonly used due to their operational characteristics and capabilities in different environments and conditions. Rotary UAV classes include mainly quadcopters, helicopters, and other types such as tricopter, hexacopter, and octocopter. The research works related to the implementation of the ADRC to rotary UAVs are illustrated in this subsection.

1) ADRC for Quadcopters

The quadcopter UAV has recently attracted a lot of attention due to its high energy efficiency, simple structure, low risk, good mobility as well as high reliability, and adaptability. The Quadcopter UAV has been adopted in many applications, such as emergency responses, military and civil fields, security, and transportation. However, from the control perspective, the quadcopter UAVs are challenging systems due to their highly nonlinear behavior, coupled dynamic model as well as underactuated structure with four inputs (four rotor speeds) and six outputs, including three linear degrees and three angular degrees of freedom. An intensive review on controlling a quadcopter UAV has been presented in [36] to illustrate the most standard controllers applied to such a system. Many conventional controllers have been implemented on quadcopter UAVs, including Proportional Integral Derivative (PID) and the linear-quadratic approach [37]–[39] model predictive control [40], adaptive control [41], [42], backstepping control [43], and fuzzy neural networks [44]. However, these techniques have limited capabilities when applying such controllers on complex systems such as UAVs. The performance and robustness levels of these control methods degrade significantly with the presence of model uncertainties since these controllers depend highly on the accuracy of the model of the plant. On the other hand, it is challenging to practically implement some robust controllers, such as the backstepping or sliding mode controllers on a real quadcopter, due to the complex structure of such control methods.

To overcome these challenges, a robust and simple control strategy based on ADRC [45] is highly recommended for such a highly nonlinear and uncertain quadrotor UAV system. As mentioned earlier, the ADRC technique framework includes two main components: the ESO to estimate the total disturbance and the feedback or nominal controller used to compensate and cancel the total disturbance. As shown in Table 2, different types of ESO and feedback controllers have been used in the ADRC structure. The various types of ESO include linear and nonlinear ESO, and the feedback controller may include linear and nonlinear State Error Feedback (SEF), Sliding Mode Control (SMC), Dynamic Surface Controller (DFC), fuzzy logic, etc.

Various structures of ADRC have been adopted in the literature. First, a linear ESO and linear SEF are widely used in the ADRC configuration [46]–[54] to control quadcopter UAVs. The attitude control problem has been considered in [46]–[49], [51]–[54] and both position/attitude control has been adopted in [47], [49]. In [47], the authors addressed the automatic carrier landing problem of the quadcopter UAV by using the ADRC for the inner and outer loop (position and attitude) in the presence of air wake turbulence f. Only simulation results have been presented in [47] to show the performance and robustness of the controller. A combination of ADRC and Embedded Model Control (EMC) has been introduced in [48] to address the attitude control problem using a linear ESO and a linear SEF. Several experimental tests have been conducted to highlight good attitude controller performance. Second, In another ADRC structure based on a nonlinear ESO and a linear SEF has been used in [55], [56], to address the guidance and position/attitude control problem of quadcopters. An ADRC guidance law has been proposed in [55] to ensure the security of quadcopter collision avoidance. The circle criterion is used to prove the stability of the nonlinear ADRC. The total disturbance considered in [55] includes wind disturbance, sensor noise, and the unknown acceleration of the dynamic obstacle. The collision avoidance in three dimensions, as well as finite time collision avoidance, were not considered in [55]. The authors in [46], [57]–[64] combined a nonlinear SEF with a linear ESO in the ADRC structure to control the position and attitude of the quadcopter UAV. The authors in [46] used the ADRC with nonlinear SEF and linear ESO in the presence of external disturbances and

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parameter uncertainties in the control of the quadcopter and studied the attitude stabilization problem. Nonlinear ADRC with both nonlinear SEF and nonlinear ESO has been used in [46], [65]–[71] to tackle the position and attitude control problems of the quadcopter. An ADRC scheme based on the swarm intelligent method is proposed in [66] to track the desired trajectory and avoid obstacles. To obtain the optimal values of the parameters of the ADRC controller, the chaotic grey wolf optimization has been used, and the virtual target guidance has been adopted for the obstacle avoidance problem. The robustness shown in the simulation results is proved by Monte Carlo tests. However, the stability systematical theory analysis has not been covered in this work.

In addition, many researchers combined the SMC controller with linear or nonlinear ESO in the ADRC configuration to take advantage of both techniques and improve the robustness performance of the quadcopter. In [56], [66], [72]–[76], SMC technique is used to design the feedback controller and to solve the position/attitude, flatness as well as robustness problems of the quadcopter UAV. The SMC controller has been combined with linear ESO in [56], [72]–[76] while the authors in [66], [77] used SMC with nonlinear ESO to build the advanced version of the ADRC technique. In [74], an SMC-based ADRC has been presented to ensure state tracking in the existence of noisy measurements. An ADRC technique using an SMC-based flatness controller has been adopted in [75] to develop a robust tracking controller for a quadcopter. The performance of the proposed controller is evaluated using simulation results only. Researchers attempted in some other works to improve the estimation performance of the ADRC scheme by introducing a higher-order ESO. In [78], [79], the ESO in the ADRC structure is replaced by a generalized ESO (GESO) to estimate more complex total disturbances. Robustness indices for the proposed observer-based control structures given in [78] show that the GESO has better performance than the ESO technique. In [79], a robust ADRC based on GESO is developed for the attitude control of a quadcopter. Although the GESO presents better performance than the ESO, it reduces the stability margin of the system. A dynamic surface control technique has been incorporated with a tracking differentiator, and ESO in [80], [81] to form a new ADRC scheme to control the quadcopter UAV. In [81], the dynamic surface control is designed using the estimate states provided by the ESO and then used to attitude control of the quadcopter. A decoupled ADRC based on dynamic surface control is also proposed in [80] to solve the trajectory tracking problems for a quadrotor. Simulation results were presented in this work to show the tracking of a cylindrical spiral trajectory. Finally, in order to take advantage of both the fuzzy controller and ADRC technique, the authors in [82] used a fuzzy adaptive controller as a feedback control along with the ESO to propose a fuzzy linear ADRC controller. The fuzzy rules have been used for the compensation term b_0 and bandwidths of the controller and the observer. In [82], all the model parameters were perturbed by 20% to evaluate the robustness of the suggested Fuzzy ADRC controller against uncertainties. The experimental results show that Fuzzy ADRC performs better than linear ADRC and fuzzy PID. However, the influence of ceiling and ground effect has not been considered in this work.

2) ADRC for single rotor (helicopter)

Single rotors UAVs have been used in military and civil applications, rescue, and surveillance. However, complex characteristics of helicopters, such as highly-inherent nonlinearities, coupling dynamics, underactuated structure, and instability, increase the difficulty of designing a suitable controller for them. Controllers such as H_∞ control [83], Adaptive control [84], Fuzzy Control [85], Neural Network control [86], and many others have been implemented to tackle the helicopter control problems. Nonetheless, these controllers are complex in structure, and they require high computation power [87]. On the other hand, simpler controllers, however, generally do not have the ability to account for the disturbances, and their performance depends on the system model. ADRC technique is seen as a perfect candidate to address the control problem of helicopters due to its simple design, as it is not highly dependent on the system model, and due to its ability to effectively estimate and reject internal and external disturbances. Researchers have implemented ADRC on helicopters by combining different types of nominal control laws and ESOs. The authors in [88]–[91] used a Linear State Error Feedback (LSEF) along with a linear ESO for helicopter attitude control. In [90] and [91], the parameters of the ADRC controller were optimized using the Artificial Bee Colony (ABC) optimization algorithm. It has been shown in [90] that the overall performance of the ADRC is superior to the Linear Quadratic Regulator (LQR) method. Also, the simulation and experimental results obtained in [91] demonstrated the advantage of the ADRC over PID and LQR. However, the ABC optimization technique suffers from a well-known problem which is premature convergence. This problem can affect the tuning process, and therefore, it can cause obtaining unoptimized parameters. The techniques reported in [88]–[91] have the advantage of the simple design of linear SEF and linear ESO where fewer parameters are required to be tuned compared to other ADRC structures. However, the control performance of such ADRC designs is questionable. Therefore, a more comprehensive analysis is required to prove the effectiveness of the proposed control paradigms proposed in [88]–[91].

On the other hand, the ADRC technique based on a Nonlinear State Error Feedback (NLSEF) control law and NLESO were proposed in [87], [92]–[95] for attitude stabilization. The work proposed in [92] took into consideration the stabilization of a slang load connected to the helicopter. The results were compared with PID control, and the improvement was significant. The same ADRC structure was used in [87], [96], [97] for different control problems. In [96], the ADRC was applied for trajectory tracking during autorotation, whereas the authors in [97] and [87] implemented ADRC to control the rotational speed of turboshaft in a helicopter engine. In

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general, the nonlinear ADRC techniques similar to the works presented in [87], [92]–[95] can achieve superior UAV control performance compared to linear ADRC. However, the main drawback of such designs is the complex design of the control system.

Linear state error feedback controller with nonlinear ESO was used in [98]–[102], [102]. The goal in [99] and [98] was controlling the heading "yaw" of a helicopter, where the simulation results in [98] and the experimental results in [99] confirmed the adequacy of the proposed ADRC. In addition to the heading control, the altitude control was considered in [100] and [102]. The authors in [100] compared the ADRC performance with that of a robust nonlinear feedback controller and a Backstepping controller. The author concluded that both Backstepping and ADRC provide the best performance and that the ADRC is considered the best candidate since it is a model-free method that does not require knowledge of the plant dynamics (or requires minimum information). In [101] the effectiveness of the ADRC for attitude control without velocity measurements has also been demonstrated by both simulation and experimentation. The work in [102] dealt with the helicopter position tracking problem.

Artificial Intelligence (AI) has also been implemented to boost the capabilities of ADRC. A Radial Basis Function (RBF) observer has been used in [103] along with an NLSEF to control the tail rotor speed of a helicopter without the need for the parameter's value. The simulation test results showed that the propulsion system is able to achieve fast dynamic response and aerodynamic disturbance rejection. In the same work, the authors also guaranteed the stability of the controller by using the Lyapunov theorem. The drawback of AI-based techniques such as the work proposed in [103] is that AI-based controllers require a substantial dataset for training and validating the results.

Other related research works combined backstepping control with a Linear ESO [104]–[106]. The authors in [104] and [106] discussed the trajectory tracking problem and proved the stability of the closed-loop system using Lyapunov's theorem and input-to-state stability, respectively. In [107] the trajectory tracking problem was considered, and a control law with the finite-time reaching stability has been synthesized using the added power integrator method. The disturbance estimation in [107] is performed using a Sliding Mode Observer (SMO). To show the advantage of using a robust controller instead of an LSEF control law in ADRC structure, the authors in [108] experimentally compared SMC law with LSEF for 2DOF helicopter position control, where a Generalized Proportional Integral Observer (GPIO) was used. The results favor the precedence of the SMC over the LSEF control law.

3) Other rotary UAVs

In [109], the author presented a novel hexacopter design in which the rotor sections were made to tilt around their respective arm. This created independent forces in x and y axes that decoupled the translational and rotational dynamics. An ADRC controller formed from an NLSEF control law and an NLESO for estimating the disturbances is used in each of the six decoupled loops. The obtained simulation results showed that the ADRC tracking error is lower than that of the PID controller. Works given in [110], [111], and [112] proposed LSEF control law and a LESO for controlling the rotational dynamics -inner loop controller- in a cascaded position controller. research in [110] focused on the control of a hexacopter platform that is equipped with a two-degree-of-freedom robot arm. The simulation and flight test results demonstrated the superiority of using ADRC over the cascaded PID controller. Also, it is shown in [110] that third-order ADRC has a better performance than second-order ADRC when the disturbance acts in both the roll and pitch axes. The authors in [111] and [112] demonstrated the strength of using an ESO by evaluating the capabilities of a baseline controller and the same baseline controller equipped with an ESO through simulation and flight tests on a hexacopter. An attitude control scheme based on a fuzzy adaptive ADRC (using a linear ESO) was developed in [113] to address issues of a flying robot's visual servoing such as the sluggish response speed and anti-interference weakness. A comparative study of the performance of the proposed ADRC scheme, conventional linear ADRC, PID, and Fuzzy-PID was carried out in [113] by simulation experiments to demonstrate the effectiveness of the proposed ADRC scheme. An ADRC scheme based on NLSEF control law and an NLESO was proposed in [114] to control the attitude and the $z-axis$ velocity of a spherical UAV. The comparison with PID through simulation showed that ADRC has better performance and robustness against disturbance and unmodeled dynamics.

Table 2 below summarizes ADRC research works discussed above and implemented on rotary UAV systems.

B. ADRC FOR FIXED-WING UAVS

The second type of UAV system, which is the fixed-wing UAV, is witnessing a growing interest in several applications, especially in imagery as a case in point. This increasing demand for using fixed-wing UAVs in various applications is due to several advantages of fixed-wing UAVs over rotary UAVs. A substantial advantage of fixed-wing UAVs is the low energy consumption of a fixed-wing UAV compared to a rotary UAV. Since UAVs are mainly hovering over a specific area for some period of time, the rotary UAVs, such as the quadrotor UAVs, will constantly require energy to keep the wings spinning in order to retain hovering as shown in Figure 4-a. However, as shown in Figure 4-b, for a fixed-wing UAV, the lift of the UAV is generated passively as its wings cut through the air at a specific angle. Thus, fixed-wing aircraft have the ability to travel longer distances with less energy consumption compared to rotary UAV systems.

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TABLE 2. Summary of the ADRC works implemented on rotary UAV systems

Type of Rotary UAV	References	ADRC Approach		Validation		Control problem
		Controller	Estimator	Simulation	Exp.	
Quadcopter	[46]–[54]	LSFE	LESO	[46], [47], [49]–[52], [54]	[48], [51], [52]	Attitude: [46]–[49], [51]–[54]; Position/attitude: [47], [49]
	[55], [56]	LSFE	NLESO	[55], [56]	[56]	Guidance: [55]; Position/Attitude: [56]
	[46], [57]–[64]	NLSEF	LESO	[46], [57]–[64]	[61]	Attitude: [46], [57], [58], [61]–[64]; Position/attitude: [59], [60]
	[46], [65]–[71]	NLSEF	NLESO	[46], [65], [66], [68]–[71]	[67], [68],	Attitude: [46], [66]–[71] Position/attitude [65]
	[56], [72]–[76]	SMC	LESO	[56], [72], [73], [75], [76]	[71] [74]	Position/attitude: [56], [72]–[74] Robustness [75], [76]
	[66], [77]	SMC	NLESO	[66], [77]		Guidance: [66]; Robustness [77]
	[78], [79]	LSEF	GESO	[78]	[79]	Attitude: [78]; Robustness [79]
	[80], [81]	DSC	LESO	[80], [81]		Attitude [80], [81]
	[82], [115]	Fuzzy	LESO	[115]	[82]	Attitude [82], [115]
Helicopter	[88]–[91]	LSEF	LESO	[88], [90], [91]	[91]	Attitude: [88]–[90]; Yaw: [91]
	[98]–[102]	LSEF	NLESO	[98]–[102]	[99], [101]	Attitude: [99], [101] Yaw: [98], [100] Altitude: [100] Position: [102]
	[87], [92]–[97], [116], [117]	NLSEF	NLESO	[87], [92]–[97], [116], [117]		Attitude: [87], [92]–[95] Position: [96], [116] Turbine shaft speed: [97], [117]
	[103]	NLSEF	IESO	[103]		Tail rotor speed
	[104]–[106]	BS	LESO		[104]–[106]	Position: [104], [106] Attitude/altitude: [105]
	[107]	FT	SMO	[107]		Position
	[118], [119]	BS	NLESO	[118], [119]		Position: [118] Attitude: [119]
	[108]	SMC	GPI		[108]	Attitude
	[120]	SMC	SMO	[120]		Attitude
Other rotary types	[110]–[112]	LSEF	LESO	[111]	[110], [112]	Position
	[109], [114]	NLSEF	NLESO	[109], [114]		Position: [109] Attitude and z-velocity: [114]

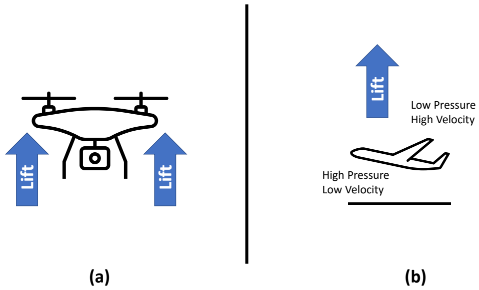

FIGURE 4. **The lifting methodology adopted by (a) Rotary UAVs (b) Fixed-wing UAVs**

Due to the above-mentioned attractive advantage of the fixed-wing UAV, controlling these systems has become a top research topic in the area of UAV control. Several attempts to control the flight of a fixed-wing aircraft were reported in the literature using basic control strategies such as PID controllers and their invariants [121], [122], fuzzy-based controllers [123], and Neural Network-based controllers [124]. However, as discussed earlier in the introduction section, these basic control systems cannot deal effectively with the uncertainties and disturbances of a complex non-linear MIMO UAV system. Therefore, the ADRC mechanism and its variants have been widely adopted to control UAV systems, including fixed-wing UAV systems. Table 3 shows a brief summary of the abovementioned research works proposing ADRC and its variants to control fixed-wing UAV systems.

As outlined in Section III, the ADRC is comprised of two main components, the state error feedback controller and the ESO. Based on Table 3, there are only a few techniques that chose to adopt linear state error feedback controller or linear ESO [128], [135], [140]. The main reason is due to the limited ability of linear control paradigms to efficiently control a non-linear complex system such as a fixed-wing UAV aircraft. However, it is always valid that there is still an advantage of using linear control systems which is simplicity. Meanwhile, the performance of a linear controller can be enhanced by involving other mechanisms or optimization techniques to strengthen the overall control system. In [128], a flying boat is being controlled using ADRC based on a linear state error feedback controller with Tagaki-Sugeno (T-S) fuzzy reasoning technique. Simulation results demonstrated the efficiency of the suggested control method and the flying boat was able to take off under three different wave conditions: irregular waves, regular waves, and calm water. In [135], a control system composed of a framework of a Model Predictive Control system (MPC) and ADRC was proposed to control a fixed-wing UAV to follow a pre-defined path under various disturbances. In the proposed control system, the state error feedback controller and the ESO were both linear. Moreover, the proposed control system implemented an augmented state-space model to design the predictive controller, and Hildreth's Quadratic Programming Procedure was utilized to solve constrained problems in the system.

However, most of the work performed in the area of ADRC with fixed-wing UAVs is based on non-linear state error feedback controller as well as non-linear ESO [125]–[127], [129], [130], [132], [134], [136]–[139], [142]. This is expected since a non-linear control paradigm can efficiently deal with the complex non-linear nature of a fixed-wing UAV system. In [125], an NLSEF-NLESO control system was proposed to deal with the wind disturbances problem that faces small fixed-wing UAVs when landing. The proposed ADRC controller was experimentally implemented on a small fixed-based UAV and showed acceptable landing performance as the difference between the desired altitude and the actual altitude was less than one meter, while the error between the desired pitch and the actual pitch was less than two degrees. Another NLSEF ADRC system is proposed in [126]. In the proposed control system, three ADRC controllers were implemented to control the roll, pitch, and speed of the UAV. The coupling between the decoupled control loops was treated as unmodeled dynamics, which was estimated using an NLESO. The proposed altitude and speed of ADRC controllers were experimentally implemented on three "Skywalker" UAVs which showed good performance in following the trajectory. In [127], a framework of ADRC and PID was proposed to control the altitude of a fixed-wing UAV. The proposed work was based on the observation that fixed-wing UAVs were exposed to significant coupling, nonlinear behaviors, and critical major variations in steering effectiveness while hovering. The controlled variables of the proposed adaptive control strategy were the orientation angle and the angular velocity. The NLSEF ADRC was implemented in an outer loop to control the orientation angle, while the angular velocity was controlled using a PID controller in the inner loop. To overcome the challenge of high-frequency jitter in the classical ADRC scheme, a particular nonlinear function is utilized to enhance the control system. Simulation results have shown that the overshoot of the altitude control system was below 1%, while the adjustment time was within a maximum of 2 seconds. A real experimental flight test was also conducted to prove the efficacy of the suggested control system.

C. ADRC FOR HYBRID UAVS

A UAV can include both rotary and fixed wings, mainly to be able to achieve vertical take-off and landing. Therefore, hybrid UAVs are also widely known as Vertical Take-Off and Landing aircraft (VTOL). Table 4 summarizes the existing research works dealing with ADRC and its variants developed to control hybrid UAVs. Some of these works were based on a linear state error feedback controller and a linear ESO [145]–[148]. In [145], the path-following problem of a hybrid UAV was achieved using a linear ADRC, where a non-linear error model was created using the modified Rodrigues parameters while observing the dynamics of the servo motors. Then, a multi-level control system was implemented to create the translational and rotational controllers based on the time-scale property of each subsystem. A linear ESO

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TABLE 3. Summary of the ADRC works implemented on Fixed-Wing UAV

Ref.	ADRC Approach		Validation		Comments
	Controller	Estimator	Sim.	Exp.	
[125]	NLSEF	NLESO	Yes	Yes	Landing Control
[126]	NLSEF	NLESO	Yes	Yes	Altitude Control for Skywalker UAV
[127]	NLSEF	NLESO	Yes	Yes	Altitude Control
[128]	LSEF	NLESO	Yes	No	ADRC and Tagaki-Sugeno (T-S) fuzzy reasoning are applied to control a flying boat system
[129]	NLSEF	NLESO	Yes	No	The ADRC parameters were optimized using Genetic Algorithm. The simulation model was the F15 plane
[130]	NLSEF	NLESO	Yes	Yes	Landing control
[131]	NLSEF	NLESO	Yes	No	Both the translation and rotation are controlled using ADRC
[132]	NLSEF	NLESO	Yes	No	The steady-state error of the altitude was reduced by 0.0235m, while the setting time was reduced by 8.2s
[133]	LSEF	NLESO	Yes	Yes	Both the translation and rotation are controlled using ADRC
[134]	NLSEF	NLESO	Yes	No	Altitude control based on ADRC and multi-object non-linear control allocation
[135]	LSEF	LESO	Yes	No	Obstacle avoidance control
[136]	NLSEF	NLESO	Yes	No	Comparison between ADRC and LADRC
[137]	NLSEF	NLESO	Yes	No	An auto-landing control scheme consists of a longitudinal and lateral auto-landing control systems
[138]	NLSEF	NLESO	Yes	No	Trajectory tracking control
[139]	NLSEF	NLESO	Yes	Yes	Path following controller implemented on Snow Goose drone
[140]	LSEF	LESO	Yes	Yes	ADRC applied on a bird-like Flapping Wing Micro Air Vehicle (FWMAV) drone during automatic landing
[141]	NLSEF	LESO	No	Yes	Altitude control for the dove flapping wing micro air vehicle in intermittent flapping and gliding flight
[142]	NLSEF	NLESO	Yes	No	Altitude controller for FWMAV UAV
[143]	BS	NLESO	Yes	No	Tracking the reference trajectory for an Airship
[144]	LSEF	NLESO	Yes	No	Autonomous Landing for Unmanned Seaplanes. Both LSEF and NLSEF were implemented

and an auxiliary observer were utilized to compensate for all possible uncertainties. In the end, the singular perturbation theory was adopted to analyze the stability of the overall system. This method proposed in [145] was validated with simulation only to evaluate its performance and show its efficacy. Another linear ADRC system was proposed in [146] for Autonomous Aerial Refueling (AAR). First, the receiver plane of the AAR was modeled, and the disturbances were generated. Three second-order systems and a third-order system were developed to represent the longitudinal and lateral models of the receiver plane, respectively. This made the motion model more convenient for controller design, and the scale separation was avoided in the meantime. Later on, the ADRC was implemented into the docking controller design to show its robustness against the various disturbances during the docking of AAR. A comparative study of simulation results carried out in [146] proved that the ADRC strategy outperformed other control techniques to successfully control the AAR docking in the presence of complex disturbances.

Due to the complexity of the VTOL systems, other related works proposed ADRC structures based on NLSEF and NLESO [149]–[152]. In [149], the hovering control of a tailsitter UAV was presented. The tailsitter UAV consisted of one flying wing, two actuators, and two elevons. The work also developed a six-degrees-of-freedom (6-DOF) model of the tailsitter. To ensure advanced performance in hovering and vertical flying, the ADRC was adopted to design an altitude controller. The objective of the ADRC system was to decouple the system model into a controllable chain of integrators using signals generated from the ESO and the Tracking Differentiator (TD). Using the decoupled system dynamics, the hovering of the tailsitter can be achieved by developing a simple position controller. This work conducted some experimental tests and showed good tracking results. In [152], a control system that utilized a differential propeller thrust to control the lateral direction was proposed for unswept flying-wing UAVs. The objective was to overcome the on-ground lateral direction control problem without rudder, steering, or braking mechanisms. First, an analytical model of the hybrid UAV on-ground moving was created. Then, the NLSEF-based ADRC theory was used to develop a yaw angle controller by adopting the differential propeller thrust as the control output. In the end, a straight path-following control system was implemented by enhancing the vector field path-following technique. Based on the conducted real experiments, the proposed control system has several advantages, including better precision, robustness, and shorter response time compared to other techniques. Moreover, the proposed control system had reduced computational complexity with a simple parameter setting process.

The comprehensive discussion in Section IV has clearly shown that both, nonlinear and linear ADRC structures have been widely implemented for UAV applications. This is an indication that both strategies have their own strong aspects and advantages. The nonlinear and complex nature of the system uncertainties and disturbances presented within a UAV system has presented the nonlinear ADRC as a highly efficient control method with strong capabilities to counter nonlinear

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TABLE 4. Summary of the ADRC works implemented on hybrid UAV systems

Ref.	ADRC Approach		Validation		Comments
	Controller	Estimator	Sim.	Exp.	
[149]	NLSEF	NLESO	No	Yes	Autonomous landing of unmanned seaplanes
[145]	NLSEF	LESO	Yes	No	Trajectory tracking problem of VTOL drone
[153]	NLSEF	LESO	No	Yes	Practical control implementation of Tri-TiltRotor flying wing
[154]	NLSEF	LESO	Yes	No	ADRC method is implemented for a Joined-Wing UAV
[150]	NLSEF	NLESO	Yes	Yes	ADRC for loitering unit with parameter uncertainty
[151]	NLSEF	NLESO	Yes	No	Altitude controller for loitering munition
[152]	NLSEF	NLESO	No	Yes	On-ground lateral direction control of the Unswept flying-wing UAV
[146]	LSEF	LESO	Yes	No	Autonomous Aerial Refueling (AAR)
[155]	LSEF	NLESO	Yes	Yes	solving the lateral-directional control problem without an aileron and rudder
[147]	LSEF	LESO	No	Yes	Automatic landing control of a Very Flexible Flying Wing
[148]	LSEF	LESO	No	Yes	Trajectory control of a Very Flexible Flying Wing

characteristics. The nonlinear functions of the main control law, as well as the state observer, are the driving force behind the strong capabilities of the nonlinear ADRC controllers. Alternatively, linear ADRC controllers are also utilized in UAV systems, offering the main advantage of a simpler design structure compared to nonlinear ADRC. A nonlinear ADRC control design contains a substantial amount of tuning parameters. Therefore, the stability analysis becomes more challenging. As a result, linear ADRC is favored in several control systems presented in previous research studies because of the smaller number of tuning parameters and simpler analytical analysis. Moreover, findings from research in [156] demonstrate that linear ADRC controllers can achieve superior levels of robustness than nonlinear ADRC developed for a basic robot system that is exposed to parameter variations and abrupt disturbances. In the experiment conducted in [156], both linear and nonlinear ADRC schemes were implemented to command the positioning of a flexible single-link arm. Results showed that the nonlinear ADRC generally exhibited superior dynamical behavior compared to the linear one under basic conditions. However, the linear ADRC outperformed the nonlinear one in terms of the disturbance rejection and robustness characteristics.

V. ILLUSTRATIVE EXAMPLE: IMPLEMENTATION OF ADRC FOR QUADCOPTER

The quadcopter system is selected in this section to demonstrate the implementation and performance of the ADRC strategy. Quadcopters are among the most popular classes of UAVs. They are considered good benchmarks to develop, implement and test sophisticated flight control schemes thanks to their fast and easy maneuverability and significant control properties. Quadcopters are naturally nonlinear and highly coupled systems actuated by four independent rotors arranged in a cross or plus shape as shown in Figure 5. This results in independent elevation, roll, pitch, and yaw movements enabling the UAV to hover, take off, and land vertically, in addition to performing aggressive maneuvers.

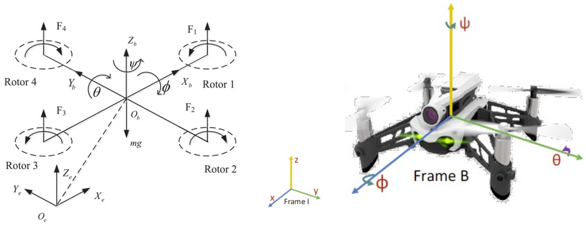

FIGURE 5. Parrot mambo drone

The linear position is specified in the inertial frame x, y, z axes with $\xi = [x, y, x]^T$, while the angular position is defined in the inertial frame with $\eta = [\phi, \theta, \psi]^T$. Note that the Roll angle ϕ defines the rotation around the x-axis; and the pitch angle θ. It also determines the rotation around the y-axis and the yaw angle ψ; around the z-axis. The quadcopter rotors generate aerodynamic thrust force and moments . Generally, the quadcopter system consists of two main subsystems: position and attitude subsystems. The position subsystem can be described by the following dynamic equation [157]:

$$m\ddot{\xi} = G + R\,T_B \tag{4}$$

where m is the mass of the quadcopter; G is a vector that includes the gravity effect g and is given by $G = \begin{bmatrix} 0 & 0 & g \end{bmatrix}^T$; T_B is given by $T_B = \frac{T}{m}$ where T is the total thrust of the rotors created in the direction of the body z-axis and R is

$$R = \begin{bmatrix} C_\psi S_\theta C_\phi + S_\psi S_\phi \\ S_\psi S_\theta C_\phi - C_\psi S_\phi \\ C_\theta C_\phi \end{bmatrix} \tag{5}$$

The dynamic model of the attitude subsystem is given by

$$J\ddot{\eta} + C\left(\eta, \dot{\eta}\right)\dot{\eta} = \tau_B + \tau_d \tag{6}$$

where J is the diagonal moment of the inertia tensor matrix and C is the Coriolis matrix term, containing the gyroscopic and centripetal terms defined in [157] and τ_d represents the external disturbances that the system is subjected to. In this illustrative example, the ADRC technique is applied for attitude control, so the dynamic equation (6) can be written as follows:

$$\ddot{\eta} = -J^{-1}(C\left(\eta, \dot{\eta}\right)\dot{\eta} + \tau_d) + J^{-1}\tau_B \tag{7}$$

The dynamic model can be rearranged as follows

$$\ddot{\eta} = f + bu \tag{8}$$

where $b = J^{-1}$ the input gain matrix and $u = \tau_B$ is the input torque. The total disturbance $f = -J^{-1}(C(\eta, \dot{\eta})\, \dot{\eta} + \tau_d)$ is a nonlinear function that incorporates the Coriolis and coupling terms as well as the external disturbances that may include -but not limited to- vertical wind gusts and air turbulence induced by the propellers at near earth flights such as land and takeoff. The state space model can be obtained from the differential equation above as follows:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f + bu \end{cases} \tag{9}$$

where $x_1 = \eta$; $x_2 = \dot{\eta}$ are the state variables; Let us define an extra state, representing the total disturbance $x_3 = f$. Thus the extended state space model obtained is given by

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 + bu \\ \dot{x}_3 = h \end{cases} \tag{10}$$

where $h = \dot{f}$. Note that the main purpose of adopting the ADRC technique is to obtain a proper estimation of the total disturbance from the ESO and then cancel it through the following feedback controller.

$$u = b^{-1}\left(-\widehat{x}_3 + u_0\right) \tag{11}$$

where $\widehat{x}_3$ is the estimate of x_3 [45], while the input gain in this particular application is defined directly from the mathematical model in (7) as $b = J^{-1}$. u_0 is the auxiliary control variable defined by

$$u_0 = \ddot{\eta}_d + K_{p_0} e + K_{d_0} \dot{e} \tag{12}$$

where K_{p_0} and K_{d_0} are diagonal positive definite gain matrices; η_d is the desired angular position and $e = \eta_d - \eta$ is the tracking error. By using the control law (11) and considering a good estimation of the total disturbances, equation (8) becomes $\ddot{\eta} = u_0$, then substituting u_0, the error dynamics can be obtained as follows:

$$\ddot{e} + K_{d_0} \dot{e} + K_{p_0} e = 0 \tag{13}$$

It should be mentioned that the error dynamics is asymptotically stable since K_{p0} and K_{d0} are diagonal positive definite gain matrices. The control scheme for the entire system is illustrated through the block diagram given in Figure 6.

The entire control scheme of the quadcopter generally consists of two main loops: an inner loop used for the attitude control and an outer loop for the quadcopter position control. In this section, a PID controller is utilized in the outer loop, while in the inner loop, two different controllers, namely PID and ADRC, are going to be tested and compared. The PID control law used here has a parallel structure of the following form:

$$u = K_p e + K_i \int e + K_d \frac{de}{dt} \tag{14}$$

where e is the tracking error and u is the PID controller output;K_p, K_i, and K_d are the PID gains.

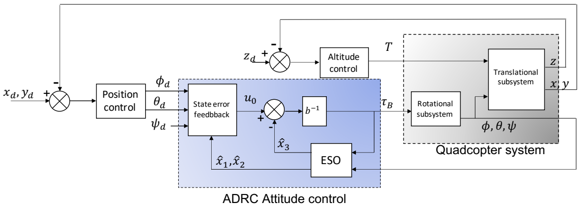

FIGURE 6. **Quadcopter ADRC control scheme**

The performance of both the inner (rotational subsystem) and outer (translational subsystem) loops, in terms of the tracking and disturbance rejection, is evaluated by simulation tests carried out on a Parrot quadcopter. Simulink Support Package for Parrot Minidrones is used to apply the PID and the proposed ADRC for attitude control. For the purpose of showing the effectiveness of the ADRC approach to successfully control the attitude in the presence of disturbances, a comparison with the well-known PID controller is performed. To this end, two simulation tests were carried out on the entire closed-loop system. In the first test, both PID controllers of the inner and outer loops were implemented. In the second test, the same PID position controller in the outer loop along with the proposed ADRC in the inner loop. The simulation results obtained for both tests under disturbance applied after 15 seconds are shown in Figures 7, 8, 9 and 10.

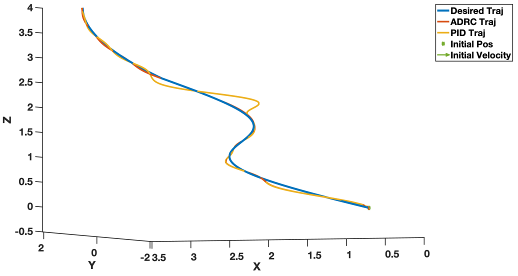

FIGURE 7. **3D position trajectory tracking**

The 3D position trajectory tracking results obtained for both tests are depicted in Figure 7. It can be observed from this figure that the ADRC used in the rotational subsystem achieves better results than the conventional PID. These results are confirmed by Figure 8 which shows the tracking in the x-position, y-position, and z-position and the corresponding tracking errors. According to Figure 8 (b), (d), and (f), the tracking error for the ADRC technique does not exceed 0.4m in the x-position, 0.2 m in the y-position and 4% in the z-position while it reaches 0.1m in the x-position, 0.2 m in y-position and 4% in z-position for PID technique. Regarding the rotational subsystem, Figure 9 shows the attitude tracking in ϕ-direction, θ-direction, and ψ-direction as well as the corresponding tracking errors. It is clear from this figure that the ADRC outperforms the PID controller in terms of both

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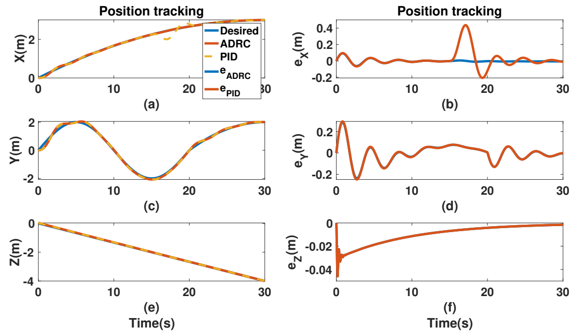

FIGURE 8. Position Tracking control with ADRC vs PID-based attitude control:

(a) x-position tracking results (b) x-position tracking error (c) y-position tracking results (d) y-position tracking error (e) z-position tracking results (f) z-position tracking error

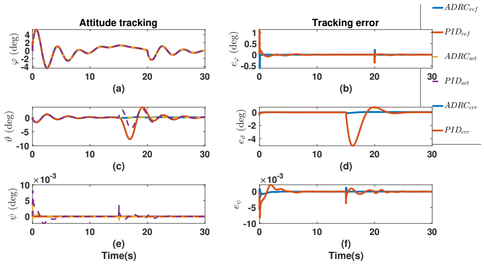

FIGURE 9. ADRC vs PID Attitude Tracking control:

(a) ϕ tracking results (b) ϕ tracking error (c) θ tracking results (d) θ tracking error (e) ψ tracking results (f) ψ tracking error

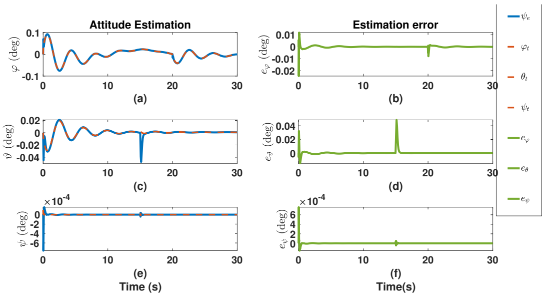

FIGURE 10. ADRC Attitude Estimation:

(a) ϕ estimation (b) ϕ estimation error (c) θ estimation (d) θ estimation error (e) ψ estimation (f) ψ estimation error

tracking and disturbance rejection capability. As mentioned earlier, the ADRC structure includes an estimator ESO used to estimate the total disturbance. The estimation tracking results for the roll, pitch, and yaw angles are shown in Figures 10 (a), (c), and (e), while the estimation errors between the true and the estimated values are given in Figures 10 (b), (d), and (f), which shows that the error dynamics is asymptotically stable with a maximum value less than 2%. All the above results show the superiority and efficacy the ADRC approach in achieving the desired performance for complex UAV systems under different disturbances.

VI. CONCLUSION

In conclusion, this comprehensive review paper examined various active disturbance rejection control (ADRC) structures implemented in unmanned aerial vehicle (UAV) systems, encompassing rotary UAVs, fixed-wing UAVs, and hybrid UAVs. The ADRC approach involves real-time estimation of the total disturbance using an Extended State Observer (ESO), followed by incorporating the estimated disturbance into a suitable feedback controller to achieve the desired closed-loop performance. The ADRC technique has proven to be a promising alternative to PID control, demonstrating successful applications across diverse domains. A review of various linear and nonlinear ADRC structures is presented in this paper for many types of UAVs, including quadcopters, helicopters, fixed-wing, hybrid, etc. Due to space limitations, discussing all related works has not been feasible. However, the most significant research works related to the application of the ADRC approach to UAV systems are considered. To advance this field further, some future research directions can be identified and explored. First, combining ADRC with vision-based techniques and Artificial Intelligence (AI) could be considered to build up smart and intelligent controllers for highly complex systems such as UAVs. This combination allows UAVs to analyze visual data in real-time for better obstacle avoidance, target tracking, and navigation in dynamic environments. Second, investigating fractional ADRC methods may provide improved robustness and performance in UAV control systems. The main aim of this future research is to explore and develop new theoretical frameworks for Fractional ADRC approaches to enhance UAV performance and disturbance rejection. Lastly, investigating the application of ADRC to networks of UAVs presents a promising research direction. This potential research work involves developing cooperative ADRC-based algorithms that allow multiple UAVs to work together, share essential information, and coordinate their actions. These advancements could significantly enhance the performance of UAVs in complex and risky missions such as surveillance, search and rescue, and environmental monitoring.

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SOFIANE KHADRAOUI received the Engineering and Magister degrees in Automatic Control from Abou Bekr Belkaïd University, Algeria, in 2004 and 2007, respectively. In 2012, he was awarded Ph.D. degree in Automatic Control by the University of Franche-Comté, France. From 2012 to 2015, he was a Postdoctoral Research Associate at Texas A&M University at Qatar. In 2015, he joined the Electrical Engineering department at the University of Sharjah, UAE, where he is currently an Associate Professor. His main research interests mainly include robust control design for uncertain systems, active disturbance rejection control, data-based control design for unknown systems, process monitoring and fault detection, compensation of nonlinearities, modeling of uncertainties, optimization and interval computation.

RAOUF FAREH received Ph.D and master degrees in electrical engineering from the University of Quebec (Ecole de technologie superieure) Canada in 2008 and 2013, respectively. He then joined Ottawa University in 2013 as a postdoctoral researcher. He joined the University of Sharjah, UAE in 2014. Currently, Dr. Fareh is an Associate Professor at the University of Sharjah 2014, where he is teaching courses related to robotics and control systems. His research interests include control and path planning for various types of robotic systems such as Manipulator, Mobile Robot, Mobile Manipulator, Parallel robots, Exoskeleton Robot, Drones, etc. In control theory, his research interests include mathematical modeling, Linear and Nonlinear control such as Active Disturbances Rejection Control, distributed control, Fractional Control, Sliding mode control, Synergetic control, etc. In addition, He is working on path planning for robotic systems using vision and image processing. He is a member of Autonomous Robotics and Active Vision Research Group at the University of Sharjah and collaborates with Power Electronics and Industrial Control Research Group (GRÉPCI) in ETS, Canada, as well as BioRobotics Lab at the University of Wisconsin-Milwaukee, USA.

MOHAMMED BAZIYAD received his Master degree in Computer Engineering from the University of Sharjah, Sharjah, UAE in 2020. Currently Eng. Mohammed is a Research Assistant at the Autonomous Robotics & Active Vision (ARAV) Research Group at the University of Sharjah. Eng. Mohammed is currently involved with many research projects in different areas mostly related to robotics. Research interests include information security, steganography, active computer vision integration, nonlinear robotic control, robot tracking/path planning, simulating human emotion for robotics, advanced software architectures for decision making, stereo and color analysis for dynamic obstacle avoidance and navigation.

MAHMOUD BAKR ELBELTAGY received his BSc in Mechanical Engineering from the University of Sharjah in 2022. He is currently pursuing an MSc at the University of British Columbia - Okanagan in Canada. His research interests include artificial intelligence, data mining, algorithms, control systems, and robotics, with expertise in prediction, machine learning, and supervised learning.

MAAMAR BETTAYEB received the B.S., M.S., and Ph.D. degrees in Electrical Engineering from University of Southern California, Los Angeles, in 1976, 1978 and 1981, respectively.He worked as a Research Scientist at the Bellaire Research Center at Shell Oil Development Company, Houston, Texas, USA. From 1982 to 1988, He directed the Instrumentation and Control Laboratory of High Commission for Research in Algeria. In 1988, He joined the Electrical Engineering Department at King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia. He has been Professor at University of Sharjah UAE since August 2000. He is the Vice Chancellor for Research and Graduate Studies at University of Sharjah, starting September 2014. He is also the Chair of the IT Governance Committee of University of Sharjah. He has published over 350 journal and conference papers in the fields of control and signal processing. He has also supervised over 50 M. Sc. and Ph. D. students. He contributed to the design and development of several curricula for Universities in the Gulf countries, Asia and Africa. His recent research interest is in process control, fractional dynamics and control, soft computing, renewable energies and engineering education.

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