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TOPICAL REVIEW

Digital Twins and Control Theory: A Critical Review on Revolutionizing Quadrotor UAVs

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ABSTRACT This work explores the crucial roles that control theory and digital twins play in enhancing the performance of underactuated quadrotor unmanned aerial vehicles (QUAVs). It describes how the novel idea of digital twins combined with control theory could alter operations. Some basic ideas, such as the underactuated UAV model, various control schemes, and innovative techniques to improve autonomy and performance in QUAV missions in dynamic circumstances, may also be of interest to readers. It highlights recent developments and presents a game-changing idea of combining digital twin with computer vision, amalgamating artificial intelligence and internet of things like elements to improve sensing and perception better for autonomous flight control, human-UAV interaction, energy-efficient flight, and swarming UAVs. The reader may finally find suggestions for applying control theory and understandings of how incorporating digital twin technology could boost its revolutionary potential.

INDEX TERMS QUAVs, optimization, control systems, machine tools, digital twin, AI.

I. INTRODUCTION

'Underactuation' or 'Underactuated system' are the terms used for quadrotor unmanned aerial vehicle. This is because of its four control inputs which are less than its six degrees of freedom (DOF). This imbalance makes this mechatronic system extremely challenging to stabilize but still they are utilized in different domains because of several reasons such that their low power consumption, low cost, and flexibility in displaying natural dynamic motion. Researchers have been evaluating this mechatronic system for different tasks like hovering, set pint regulation and helical trajectory tracking by simulating and implementing hybridized control techniques. Regretfully, the uncertainties and dynamic elements that remain unmodeled are always evolving, therefore the control scheme suggested for trajectory tracking might not consistently yield superior outcomes. For control engineering specialists, this is among the causes for why the study of unmanned aerial vehicles (UAVs) equipped with quadrotors has raised concerns. With four control inputs and six degrees of freedom (DOF), an underactuated quadrotor unmanned aerial vehicle can be stabilized using a variety of control algorithms. This review paper's main goal is to redefine precision in such underactuated quadrotor UAVs using control theory and digital twins, while also addressing the limits in the field. It has been observed that control solutions combined with digital twins (DT) are never explicitly offered for underactuated systems such as quadrotor unmanned aerial vehicles (QUAVs) but are instead immediately implemented for fully actuated systems. As a result, the dynamic model's linearization requires an extra step [1], [2], [3]. Underactuated systems are incapable of being accelerated in any direction by outside forces [4], but fully actuated systems can command acceleration changes in any direction with promptitude [5], [6], [7]. For an underactuated quadrotor UAV, the stabilization and tracking tasks have been a major source of concern. Three common challenges may be identified from these tasks as mentioned below:

- Set point regulation: This involves developing a control strategy to hover or bring the states of your underactuated system to equilibrium.
- The second problem is trajectory planning, which is concerned with the control approach that includes choosing an appropriate trajectory. Stated otherwise, this will

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result in your system achieving the required configuration quality as opposed to having zero configuration quality.

- However, the last technical problem with an underactuated quadrotor UAV is that a tracking error-minimization control technique needs to be suggested. Trajectory tracking is the term for this type of control issue when it comes to leader following methods. All these issues can be resolved if there is amalgamation of digital twins with the control theory applications for underactuated quadrotor UAVs.

This review paper is split into seven sections, section I provides some background information. It also discusses main difference in brief between fully actuated and underactuated systems, and the importance of digital twins with control theory applications. In section II, one can investigate an underactuated quadrotor UAV model; in section III, one can study the control strategies used. The need of applying AI algorithms and building digital twins for underactuated UAVs to test them in various environments is discussed in Section IV. The revolutionary idea of integrating Digital twin, amalgamating Artificial Intelligence, and the internet of things (IoT) in a number of domains—UAV communication, aircraft identification, navigation, flight control, sensing, human-UAV interaction, and swarm control—is presented in section V of this review paper. The challenges and constraints are presented in section VI followed by future trends and developments in section VII. Last but not the least one may find the conclusion in section VIII. This entire organization has been illustrated in figure 1.

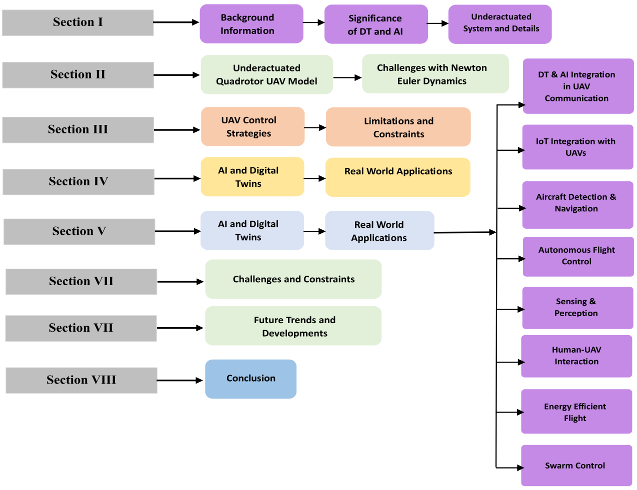

FIGURE 1. Organization of this review work.

II. UNDERACTUATED QUADROTOR UAV MODEL

This section examines the quadrotor class of unmanned aerial vehicle (UAV), which is a highly unstable system due to its underactuation. However, it also has several important qualities, such low-cost, low maintenance, and the ability to take off and land vertically. To explain its workings, it is designed as a cross with four fixed-pitched propellers and arms arranged in geometric symmetry. Regarding its airflow, it is directed downward to produce lift. Adjacent propellers must revolve counter-wise to one another for the aircraft to maintain balance while in flight and to remove the tail rotor as shown in figure 1. The four motors' revolutions per minute (RPM) are essentially used to regulate the system state variables. This will inevitably result in a change in the attitude angles, which are based on the propeller velocities. Research has shown that a quadrotor can achieve a specific altitude and attitude if it is operated with an appropriate control design [10]. For understanding the mathematical model of quadrotor UAV, one must examine traditional two frames of references- namely earth frame of reference and the body frame of reference as illustrated in figure 2 [11]. This is important because these two frames help to map the states from one frame to the other [11], [12].

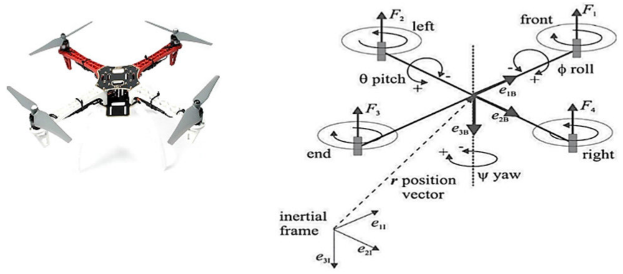

FIGURE 2. Physical and Graphical Illustration of underactuated quadrotor UAV model.

As illustrated in figure 2, the above frames help in defining the motion of quadrotor UAV. One may see earth inertial frame of reference indicated as $(E-frame)$ and the associated terms have been denoted as $OXYZ$ form where O is the origin and XYZ are three-dimensional axis with E in subscript form i.e. $(O_E, X_E, Y_E Z_E)$. This frame also supports us to derive ξ which is the linear positions of gravity as well as the Euler angles. In this figure 2, one may the other frame named as $B-frame$ which is associated with the rigid body of quadrotor UAV and therefore denoted by $(e_{1B}, e_{2B}, e_{3B}, z_B)$ where the center point of this frame is defined as axis of origin and coincides with the center of cross structure of quadrotor. Therefore, the directions have been highlighted as small case xyz with subscript B i.e. (x_B, y_B, z_B) towards front, left and up respectively. One may drive linear velocity V along with angular velocity ω and torque τ from this $B - frame$. The attitude [Roll, Pitch, and Yaw] are represented by the Euler angles $(\Theta = [\varphi\theta\psi]^T)$ which are specified by B-Frame in relation to E-Frame. Further assistance in creating the rotation matrix to map the orientation, as shown in [12] and [13], may be obtained from this.

$$D = \begin{bmatrix} c_\theta c_\psi & -c_\theta c_\psi + s_\theta c_\psi s_\phi & s_\phi s_\psi + s_\theta c_\psi c_\phi \\ c_\theta c_\psi & c_\phi c_\psi + s_\theta s_\psi s_\phi & -s_\phi c_\psi + s_\theta s_\psi c_\phi \\ -s_\theta & c_\phi c_\theta & c_\phi c_\theta \end{bmatrix} \qquad (1)$$

where $sx = sin(x)\ and\ cx = cos(x)$ in provided rotational matrix as shown above in equation (1). One may use this transfer matrix to build a relationship between the E-frame and B-Frame [12].

$$\dot{\Theta} = T\omega, T = \begin{bmatrix} 1 & t_\theta s_\phi & t_\theta c_\phi \\ 0 & c_\phi & -s_\phi \\ 0 & \frac{s_\phi}{c_\theta} & \frac{c_\phi}{c_\theta} \end{bmatrix} \quad (2)$$

where $tx = tan(x)$, it is further observed that any UAV either quadrotor usually controlled at their nearest equilibrium state because this is the state where they have all Euler angles such that roll, pitch and yaw are less than 15° and therefore the equation (2) can be further simplified as $= \Theta = \omega, T = I_{3\times3}$.

III. UAV CONTROL EVOLUTION: DELVING INTO ADVANCED TECHNIQUES

Several advanced control approaches are applied in the field of UAV control, in addition to the widely used proportional integrator and derivative (PID) control, in order to increase efficiency and consistency [14], [15], [16]. These methods work especially well with intricate and dynamic UAV systems. One well-known advanced control technique for UAV control is model predictive control (MPC). Mathematical models of the UAV's dynamics are used by MPC to predict its future behaviour [17], [18], [19], [20], [21].

Based on these predictions, control inputs are generated to optimize a predefined performance metric, such as energy consumption, stability, or trajectory tracking accuracy. MPC provides better performance by taking the UAV's complete future trajectory into account. In contrast to conventional control methods. Adaptive control is an additional remarkably sophisticated control method. To adapt, adaptive control modifies its settings in real-time. As a result, the control system can over time, consistently improve its performance even in the face of uncertainty and Unrest [22]. These cutting-edge control strategies aid in the creation of UAV control systems that are more reliable and effective. Sliding mode control (SMC) is another complex control technique that is widely used in UAV control. SMC is a nonlinear control method that performs well even when there are turbulence and uncertainties. SMC ensures stability and robustness by keeping the UAV's states inside the sliding mode, a desired operating region [22]. Lastly, several sophisticated control strategies, including neural network-based control [23] and Reinforcement learning (RL) and Deep RL (DRL) [24], are built on Machine Learning. With the use of these strategies, UAVs can gain experience and gradually enhance their control capabilities. In conclusion, the field of UAV control employs several sophisticated control strategies. These methods outperform conventional control methods in terms of performance and stability, and they are highly adapted to the intricate and ever-changing needs of unmanned aerial vehicle systems. Several UAVs can cooperate to accomplish a single mission goal by using the cooperative control technique. Cooperative control is especially useful when multiple UAVs need to coordinate and work together to complete complex tasks, such as search and rescue or surveillance [23]. SMC is a well-liked sophisticated control technique for operating UAVs. With the use of nonlinear control techniques like SMC, dependable performance is ensured even in the face of unknowns and disturbances. SMC ensures stability and robustness by keeping the UAV's states inside the sliding mode, a desired operating zone [23], [24]. The sliding surface is carefully designed to have desirable properties such as robustness against parameter fluctuations or finite-time convergence. The control law then directs and maintains the system's state trajectory at this sliding surface [24]. Chattering or its discontinuous nature is a defining characteristic of SMC [25]. The relative placement of the system states about the sliding surface activates the numerous control actions, or switching functions, that comprise the control law. When the sliding surface is absent, the control rule strongly pushes the system's state towards it by switching between different modes or control actions.

The control law changes modes to keep the system's trajectory on the surface whenever the state approaches the sliding surface [25], [26]. SMC is robust against uncertainties and disturbances throughout time because its control actions are discontinuous and swiftly adapted based on the state's proximity to the sliding surface. Furthermore, because the system behaves differently on the sliding surface in response to changes in parameters or outside disturbances, the sliding mode itself offers intrinsic resilience features. In terms of mathematics, For SMC to guarantee that the system will converge to the sliding surface and then retain its behaviour there, it is necessary to apply differential inclusion theory and Lyapunov stability analysis [26]. The first step in creating SMC components is to define a sliding surface that symbolizes the intended system behaviour.

Attractive characteristics of the sliding surface should include resilience, convergence, and stability. The dynamics of the system and the control goal determine which sliding surface is best. It is observed after reading several articles that researchers have utilized sliding surface-based control schemes and their different versions to minimize the state errors. Depending on the system dynamics and the goals of the UAV, several sliding surfaces may be employed. To reduce or completely remove the reaching mode, several sliding surface design techniques have been put forth [27]. These techniques can be categorized according to their movement algorithm's nature, dimensions, linearity, and time dependence [28]. A proportional-derivative (PD) sliding surface is naturally produced by the previously mentioned conventional sliding surface. Additionally, an essential action can be introduced to obtain PID structures. The integral term incorporation is typically done in conjunction with a boundary layer SMC approach. By adding the integral term, the steady-state error caused by the boundary layer can be eliminated [28].

Sliding surface can be classified into nonlinear constant sliding surfaces, linear constant sliding surfaces, linear discretely moving sliding surfaces, linear continuously moving sliding surfaces, and nonlinear time-varying sliding surfaces by the author of [28]. The purpose of each of these sliding surfaces is to improve controller performance by minimizing or eliminating the time required to enter the sliding phase. The second stage of the SMC design process involves determining the equivalent switching and control laws. Once the sliding surface is determined, the equivalent control law is produced to drive the system dynamics onto the sliding surface and maintain them. The comparable control rule is typically found by analyzing the dynamic equation of system, which is meant to ensure that the system exhibits desirable behaviour and satisfies the control objectives. To stabilize the system, the method involves determining a control signal that will force the system's state to follow the sliding surface. The control law needs to be developed to lessen the effects of uncertainties, disturbances, and nonlinearities in the system.

One essential element that makes sure the system's states stay on the sliding surface is the switching law. It is essential for rejecting uncertainties, disruptions, and other outside variables that could have an impact on the system's functionality. This signal forces the system to ''slide'' along a portion of its usual behaviour by using a discontinuous control signal, more precisely a set-valued control signal [29]. Switching and non-switching reaching rules are among the various types of reaching rules for SMC [29]. Moreover, a novel non-switching reaching law that demonstrates improved system robustness without raising the critical signal amplitude of the system has been described [29]. It is not necessary to switch across the sliding hyperplane in each successive step when using non switching reaching rules [30], [78]. Moreover, a new non-switching reaching law has been introduced that shows improved system robustness without raising the intensity of critical signals in the system [29]. Non-switching reaching laws ensure that there is no need to switch across the sliding hyperplane in any subsequent step [30].

UAVs may learn from their experiences and gradually get better at controlling themselves due to machine learning (ML) techniques. These techniques include RL, DRL [15], [16] and neural network-based control [15], [16]. The use of ML has been very beneficial to UAVs, allowing them to carry out their missions effectively [30], [79]. Researchers have investigated the possibilities of UAVs for delivery, surveillance, and inspection [30]. ML algorithms have yielded a variety of control solutions, including object identification, real-time path planning, and adaptive control in uncertain settings [30]. DRL is an intriguing ML-based method for controlling UAVs. Through system interaction and complicated nonlinear dynamics management, this technique enables unmanned aerial vehicles (UAVs) to autonomously identify optimum control rules [31]. DRL has remarkably confirmed success in the attitude control of fixed-wing UAVs using the original nonlinear dynamics with as little as three minutes of flying data [31]. Not only had ML integration improved UAV capabilities, but it has also lowered obstacles and opened openings for several industries [32]. Fast and trustworthy results have been obtained with this combination [32]. Traditionally, model-based control (MBC) approaches have dominated the field of UAV flight controller systems. They do, however, struggle with complexity and mostly rely on precise mathematical representations of the actual plant. The special qualities and benefits that artificial neural networks (ANNs) have in system identification and controller design make them a viable answer to these problems [32].

A detailed analysis of the combined use of MBC and ANNs for UAV flight control is conducted, with a focus on low-level control [32]. The aim is to lay the groundwork and enable effective controller designs that provide assurances of performance [32]. Unmanned Aerial Vehicle (UAV) autonomous flight control systems have been designed using fuzzy logic [33]. For example, a study on UAV flight dynamics created controllers based on fuzzy logic, both lateral and longitudinal [34]. The fuzzy logic controller performed satisfactorily even without the use of dynamic model knowledge or optimization techniques [34]. An automated flight controller for unmanned aerial vehicles (UAVs) based on Adaptive Neuro-Fuzzy Inference System (ANFIS) is another example. To control the UAV's three-dimensional position, which includes altitude and longitude-latitude location [35], this controller uses three fuzzy logic modules, which provide more stability and performance than traditional control algorithms. These methods work well for satisfying the intricate and changing needs of unmanned aerial vehicles (UAVs). Cooperative control is a technique that facilitates many UAVs collaborating to accomplish a shared mission objective. In missions where coordination and collaboration among multiple UAVs are critical, such as surveillance or search and rescue, cooperative control appears to be very beneficial [36]. To achieve common objectives, many drones must effectively coordinate and collaborate, which is known as cooperative control of UAVs [38]. The advantages of UAV swarms include increased resilience, precision, efficiency, adaptability, and reliability [39]. However, including outside communications raises the risk of running into more issues, malfunctions, ambiguities, and cyberattacks, all of which could lead to the spread of mistakes [39].

To ensure system safety and preserve acceptable performance if any of its hardware or software components malfunction or produce errors, a technique known as fault-tolerant control, or FTC, is employed [38]. These errors or malfunctions can be caused by a variety of things, such as malfunctioning sensors, actuators, lost communications, or software bugs. Identifying faults or failures and reducing their impact through control system reconfiguration or control rule adaptation is the aim of fault-tolerant control. Fault accommodation schemes, redundancy, and fault detection and isolation (FDI) approaches [39], [40], [41] can all be used to achieve this. Redundancy is the practice of keeping multiple copies of crucial software or hardware components on hand to take over in the event of a malfunction or failure. For example, a UAV may be equipped with backup sensors or actuators in case the primary one fails. To find and isolate UAV hardware or software flaws, FDI techniques leverage sensor data. To achieve FDI, a variety of tactics can be employed, including statistical techniques, observer-based approaches, and analytical redundancy.

A control approach called prescribed performance control (PPC), was created especially to meet predetermined performance standards. In PPC that stands for "prescribed performance control" it actually ensures that the tracking error converges to a predefined minuscule residual set while fulfilling a predetermined convergence rate and limiting the maximum overshoot to a small enough constant. As a result, it is successfully possible to obtain the intended transient performance measurements, including overshoot and convergence time [42]. Achieving optimal transient performance in aircraft control systems is crucial. —which include unmanned aerial vehicles (UAVs), hypersonic flight vehicles, and conventional airplanes—is emphasized in this section. It talks about several research projects and approaches that use PPC to accomplish this [42]. The study [43] focuses on the conventional PPC technique to develop an integrated guidance and control system for interceptors that guarantees exceptional transient performance during target interception. Studies [44], [45] showed that the typical PPC ensures acceptable transient performance for vehicles capable of flying above the speed of sound. It is difficult to meet the stringent beginning criterion for tracking error, nevertheless. As non-affine models, modified versions of the PPC have been proposed [46] to reduce the reliance on the original error. However, these methods may result in a large overshoot due to the selection of the beginning value of the performance function. A recently created performance function [47] is used to address this problem. The simulation findings show little to no overrun in the tracking of altitude and velocity. UAVs have a lot of promises for both military and civilian applications. Applications can do tasks more efficiently when they have good temporary performance. Many PPC-based tracking control approaches have been put forth. Reference [48] provided a tracking controller with mandated performance that is based on fuzzy-back-stepping. For just one UAV, PPC is also used in leader-follower control, platoon control, in addition to quadrotor UAVs and decentralized, finite-time, adaptive, fault-tolerant, synchronization-control multi-UAVs [49]. The simulation used in the backstepping-based investigation in [50]. Results showed that they surpassed expectations in achieving both steady-state and transient execution.

In a nutshell this section highlights the application of PPC in a range of aircraft to achieve a desired transient performance, such as UAVs, aeroplanes, and hypersonic flight vehicles. The efficacy of PPC approaches is demonstrated by the research that is cited. Through a thorough analysis of multiple literary sources, we derived table 1, which presents the limitations of each controller based on the perspectives of multiple authors.

The table lists several control strategies and the restrictions that go along with them. Despite being widely utilized, the PID approach has the potential to overshoot and requires time-consuming experimentation. Sliding Mode Control

TABLE 1. **Prescribed performance Control Techniques & their limitations.**

Control Technique	Limitations
PID [51-52]	• Experiments can take a lot of time to complete. • Aggressive gain and overshooting are possible in some circumstances. • The probability of overshoot events exists when modifying the parameters.
SMC [53-54]	• During switching, there are severe chattering effects. • Creating such a controller is a complicated process. • The sliding surface plays a major role in the sliding control method, and a poor design can lead to subpar performance.
LQR [55-56]	• Here it needs an access to all state variables • The promptness of the response cannot be guaranteed. • It is unsuitable for systems that need a consistent, minimal steady state.
Variable Gain Control [57-58]	• A lot of simulations are run to schedule gains. • Performance results are not assured.
Backstepping [59-60]	• It is not a time-efficient method. • It is susceptible to changes in the settings. • Putting it into practise can be difficult.
H-Infinity [60-61]	• It involves complex algorithms in mathematics. • Putting it into practice can be difficult. • A model that is at least somewhat accurate of the system that needs to be managed.
Adaptive control [62]	• Needs accurate model • Putting the design into practice can take some time. • Before final implementations, a significant amount of design effort is necessary.
Neuro-Fuzzy Algorithm [63]	• There is no assurance of stability. • Critical systems require constant tuning. • It uses a substantial amount of processing power. • In the presence of uncertainty, offline learning may not succeed.
Markov decision process-formulated Reward Functioning control Algorithm [134]	• The tracking results were accurate. • Position and attitude graphs show the chattering noise. • Addressed the three different types of wind disturbances; payload disturbances and rotor efficiency loss were not discussed.
Reinforcement learning based UAV formation control [135]	• Integration of Lidar based localization seems complex task to perform • Lidar sensors rely on-line-of-sight measurements, and obstructions. Thus, it might hinder Lidar's ability to accurately localize.

TABLE 1. ***(Continued.)*** **Prescribed performance Control Techniques & their limitations.**

Markov decision process (MDP)-formulated incremental RL Algorithm [136]	• Position and attitude graphs show the chattering noise. • Addressed the three different types of wind disturbances; payload disturbances and rotor efficiency loss were not discussed.
Aggressive Quadrotor Flight Using Curiosity-Driven Reinforcement Learning [137]	• A branch structure exploration strategy is also applied to guarantee the robustness of the policy and to ensure the policy trained in simulations can be performed in real-world experiments directly. • Position and attitude graphs show the chattering noise

(SMC) causes chattering sounds during switching, and for the best results, the sliding surface must be carefully designed. The Linear Quadratic Regulator (LQR) is not appropriate for systems that require minimal consistent steady state since it requires complete access to system states and may not always respond promptly. Even though gain scheduling is extensively used, it takes a lot of effort and doesn't guarantee performance outcomes. Although effective, backstepping is sensitive to configuration changes and does not save time. H-Infinity control necessitates an accurate model of the managed system and entails sophisticated mathematical procedures. Before being implemented, adaptive control requires a detailed system model and a large amount of design work. Neural Networks and Fuzzy Logic are two examples of Artificial Intelligence (AI) techniques that may not guarantee stability, require constant system tweaking, demand a large amount of computing resources, and have challenges while learning offline in unpredictable contexts.

The last four control algorithms in the table display a range of features and results in their individual uses. Tracking findings were very accurate in the Reward Functioning control system developed using the Markov Decision Process [129], however chattering noise was visible in the position and attitude graphs. Although the method effectively tackled three different kinds of wind disturbances, payload disturbances and rotor efficiency loss were not considered in the discussion. Lidar-based localization presented challenges for reinforcement learning-based UAV formation control [130], with potential obstacles arising from Lidar's dependence on line-of-sight measurements and vulnerability to obstructions. Similarly, the method known as the Incremental RL method [131], developed from the Markov Decision Process, showed chattering noise in the position and attitude graphs, and acknowledged wind disturbances but skipped over payload disturbances and rotor efficiency loss. A branch structure exploration technique was used to establish policy resilience in the context of aggressive quadrotor flight using curiosity-driven reinforcement learning [132]. This allowed the policy that was taught in simulations to be immediately applied in real-world tests. Nonetheless, location and attitude graphs showed chattering noise, as seen in the other algorithms [130], [131], [132]. To sum up, every method has advantages and disadvantages, highlighting the significance of choosing a strategy that is in line with application restrictions and requirements.

IV. DIGITAL TWIN APPLICATIONS & SIGNIFICANCE

A digital twin (DT) is simply a virtual replica of an actual system or object. It is an all-inclusive, live digital model that captures the functional and physical characteristics of the thing it represents. This covers its working conditions, geometry, and behaviour. The digital twin can replicate interactions and changes in its physical counterpart since it is updated continuously with data from sensors and other sources. Throughout the physical asset's lifecycle, this technology is widely employed in many industries for simulation, analysis, and monitoring, which improves understanding, optimization, and decision-making. Moreover, due to its disruptive potential, artificial intelligence (AI) and DT have grown in importance across a wide range of industries, encompassing robotics, automation and manufacturing, smart cities, cybersecurity, healthcare, education, energy and utilities, and robotics [64], [65], [66], [67], [68], [69]. In addition to this one may see these two things in the field of agriculture [70], logistics and transportation [71], interaction between humans and computers and natural language processing [72]. In the same way, AI and DT is essential to fix the issues arising because of unmodelled dynamic factors in an underactuated quadrotor UAV. In addition to this, it improves their object identification [73], [74], navigation [75], [76], and mission preparation [77]. Quadrotor UAVs are special kinds of aerial vehicles that have been opted for their efficiency results in several tasks [78], [79], [80], [81], [82], [83], [84]. The advancements in open-source hardware and software for quadrotor unmanned aerial vehicles (UAVs) have been demonstrated by these research contributions [85], [86], [87], [88]. Additionally, the precision of these UAVs has been redefined through optimization., Hybridizing control systems with AI and DT [89], [90], [91], [92], [93] both in conventional and traditional way [94] have enhanced the performance of quadrotor UAVs. They have been examined in virtual environment with same constraints first before going to manouver in the real time. The value of quadrotor UAVs has increased due to factors including 5G networks and the integration of clever AI recognition, detecting, and navigating algorithms [93], [94]. Thus, the researchers have been opting this subject of investigation a lot in this present time to resolve some of the critical questions as indicated in [95] where the interdisciplinary nature of quadrotor UAV research is involved.

Thus, one may say that there is a rapid growth and development in this area because of the expansion of diverse sub-mobility areas of drones. To effectively navigate the wide range of possibilities available in Quadrotor UAV research, we acknowledge the necessity for a thorough guide [96]. Quadrotor Unmanned aerial vehicles (QUAVs) are expanding quickly, and this has led to several significant research problems. One of these queries is the fact that UAV research is multidisciplinary. A variety of fields, including robotics, computer science, aerospace engineering, and remote sensing, come together while creating UAVs. To advance UAV technology, it is imperative to comprehend the ways in which different disciplines interact and to identify techniques for effective collaboration [95]. Examining the potential and difficulties posed by UAV technology is another crucial field of study. Although unmanned aerial vehicles (UAVs) offer numerous advantages such as enhanced efficiency, reduced expenses, and the ability to gather data, they also include limitations, including safety concerns, privacy difficulties, and legal frameworks. Examining these problems and developing answers will help ensure the responsible and effective integration of UAVs into society [96]. We understand the significance of tackling these research problems as UAV researchers. We hope to offer a thorough manual that helps readers explore the wide field of UAV research. We intend to create a useful resource for scholars and practitioners in this rapidly evolving subject by combining the most recent research and insights from a variety of subdomains where control theory, computer vision algorithms, artificial intelligence, and digital twins have been combined. By sharing knowledge and cooperating, we can all collaborate to advance UAV technology and see its full potential in a range of applications. Drones, also known as unmanned aerial vehicles (UAVs), raise a few pressing research problems. Investigating how AI and machine learning may enhance UAV autonomy for better performance and decision-making is crucial. A good place to start is by attempting to maneuver the drones in simulated situations [95]. Swarm intelligence is being studied in unmanned aerial vehicles (UAVs) to facilitate collaborative tasks and efficient algorithm deployment [96]. In addition, researchers are examining effective power management techniques, alternate energy sources, and ways to prolong the battery life of unmanned aerial vehicles. Under simulated examination (digital twin) are ways to enhance UAV payload capacity without sacrificing effectiveness or maneuverability, as well as ways to modify drones to carry kinds of cargo. Security issues about UAV systems against possible cyberattacks or hijacking, as well as steps to safeguard people's privacy from the improper use of UAVs equipped with surveillance capabilities, are equally significant. The safe integration of unmanned aerial vehicles (UAVs) into crowded airspace, particularly in urban areas or near airports, raises a few unresolved questions about the necessary adjustments to air traffic control systems to accommodate UAVs.

There is a study that particularly emphasizes the important benefits of using Quadrotor UAVs in animal research, as they allow for exact data collection, non-invasive monitoring, and less disturbance of wildlife habitats [97]. However, the chances of success can be increased if the same hurdles can be created in simulated environment and test the maneuvering of QUAV. At present, this study provides an extensive overview and synthesis of credible references, giving researchers the insight and tools, they require to enable them to significantly advance the field of UAV research. Ultimately, it seeks to further the advancement and potential of unmanned aerial vehicle (UAV) technology through the promotion of AI integration. and digital twin [93], environmental monitoring [93], [94], [95], [96], [97], [98], [99], [100], [101], [102], [103], [104], [105], [106], [107], [108], [109], conservation [101], [102], [103], [104], miniaturization [105], cooperative control and swarming [76], [77], [78], [79], [80] [84], as well as the transformability of system [105], [106], [107], [108], [109].

The primary objective of this section is to provide recent trends in QUAV research over the previous three years, using the Scopus database as a reliable source. Relevant search terms including "drone with digital twin," "quadrotor UAV with AI," "AI-Enabled UAVs," and "quadrotor UAVs based on digital twin" were used to query the database. The data were carefully examined to determine the main areas of research in this subject. An indicator of each study direction's importance and impact was the quantity of scientific publications linked to it. This thorough review outlines the most potential directions for further research and provides a full picture of the status of UAV research. Overall, the search results yielded 47,635 references published in the UAV sector between 2020 and 2023. The search was conducted on September 14, 2023.

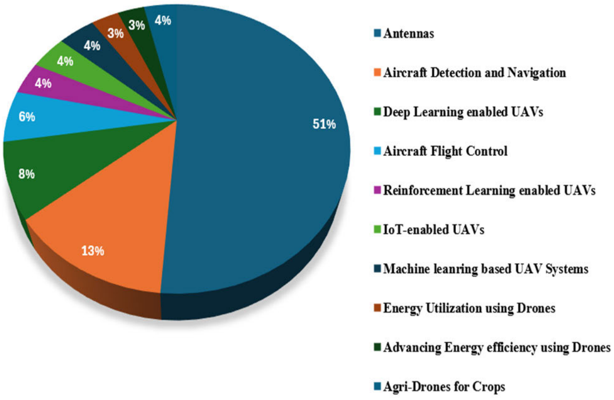

FIGURE 3. **The distribution of UAV research directions in the previous three years.**

In Figure 3, an illustration of the UAV research directions that have garnered significant interest during the last three years is presented. The amount of research on UAVs being conducted on a variety of issues has significantly increased in the previous three years. The most popular study areas now include aircraft control, the Internet of Things (IoTs), trajectories, energy utilization, aircraft identification, distant observation, multi-layered learning, reward based learning, and aerial transceivers [111].

As a result, it has been determined that digital twins and control theory are essential for tackling the major problems that quadrotor UAVs face and bringing in a new era of accuracy and efficiency. For these aerial systems, control theory offers a strong framework that regulates their dynamic behaviour, guaranteeing responsiveness, stability, and peak performance [102], [103]. A quadrotor UAV can be made more stable through the application of control algorithms, which will improve its capacity to navigate challenging terrain and react to outside disturbances. This is especially important for uses where the UAV's dependability is critical, like surveillance, search and rescue, and precision farming [104], [105], [106], [107].

Moreover, the incorporation of digital twins presents unparalleled benefits in comprehending, overseeing, and refining Quadrotor UAV functions [108], [109]. With the use of digital twins, an exact virtual model of the UAV is produced, complete with real-time sensor data, flight dynamics, and physical characteristics. This makes it possible to do ongoing analysis and simulation, which makes it possible to precisely calibrate and modify control parameters. Because digital twins may detect possible problems before they materialize in the actual UAV, they can help with predictive maintenance. This improves dependability and reduces downtime, which makes quadrotor UAV operations more effective and economical [109], [110]. Control theory and digital twins work together to handle the challenges posed by quadrotor unmanned aerial vehicles (UAVs), opening new avenues for improvements in aerial robotics.

Quadrotor UAV research has seen a significant uptick over the last three years, with a wide range of topics being investigated. The most popular research fields now include aircraft identification, distant observation, multi-layered learning, reward based learning, and aerial transceivers [111]. The creation of the previously described AI technologies has transformed the utilization of drones, resulting in enhanced capabilities in domains like object identification, trajectory optimization, and mission scheduling. Additionally, a lot of attention has recently been paid to studies on application-specific development, environmental sensing, safety and reliability, swarm behaviour, human–UAV interaction, interaction with other platforms, development tailored to a particular application, and moral and legal considerations [112]. Most of the research interest has been focused on antennas in the context of unmanned aerial vehicles (UAVs), with 22,150 publications comprising books, journal articles, conference papers, and more. Strong connections exist between this field of study and other research domains like AI, Digital twin, IoT, aviation control, remote sensing, and aircraft detection. With 7010 documents, it has been observed that there is huge utilization of AI in UAV communication domain.

This is followed by the following fields: IoT (1720 documents), aircraft control (2504 documents), remote sensing (3983 documents), aircraft detection (5604 documents), energy efficiency (1340 documents), and energy utilization (1293). Furthermore, with 1606 documents, agricultural robots have attracted a lot of attention. Figure 4 illustrates the links between various research fields, and Table 2 goes into further detail about them. These findings imply that there is a significant amount of overlap amongst UAV technology research fields, which may eventually result in more integrated and effective solutions. The information was gathered on September 14, 2023. In the areas of Artificial Intelligence (AI), Digital Twins (DT), Internet of Things (IoT), Control and Observer Design, Remote Sensing, Detection and Navigation, and Antennas/Communication, the table provides a thorough summary of the interrelationships between the many developing paths. Each cell in the table indicates the amount of interaction between the corresponding pairings of directions, quantified as numerical values.

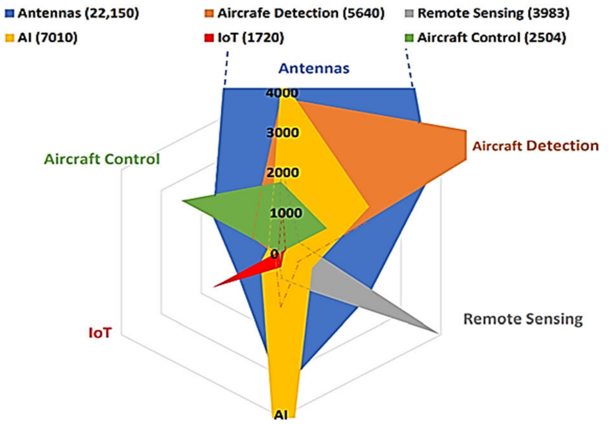

FIGURE 4. Summary of the last three years' contacts and research directions for QUAVs.

Digital twins and artificial intelligence have a lot in common, as seen by the intersection of AI & DT (7010), indicating a strong partnership in the advancement of technology. Likewise, the interaction of AI and DT with other directions emphasizes their crucial roles in advancing the IoT (0512), Antennas/Communication (4231), Control and Observer Design (294), Remote Sensing (777), Detection and Navigation (2203), and Remote Sensing (777). The table highlights the significant dependencies and cooperation among these new directions, emphasizing their interconnectedness. The values in the Control and Observer Design row, for example, highlight the interaction of these elements in the context of control systems, while the intersection of IoT with AI & DT (365) shows their mutual influence. This thorough technical overview offers insightful information about the complex relationships influencing the field of cutting-edge technologies.

V. TRANSFORMATIVE CONCEPT OF DT AND AI

The amalgamation of Artificial Intelligence (AI) and Digital Twin (DT) is a revolutionary notion that has garnered substantial momentum in various fields. Applications for this potent combination have revolutionized several industries, including UAV communication, internet of things integration with

TABLE 2. Research summary of emerging directions & mutual interactions.

Emerging Directions	Mutual Interactions					
	AI & DT	IoT	Control and Observer Design	Remote Sensing	Detection and Navigation	Antennas Communication
AI & DT	7010	512	294	777	2203	4231
IoT	**365**	**1720**	**43**	**63**	**133**	**1092**
Control and Observer	311	43	2504	0	1152	1707
Remote sensing	**707**	**63**	**0**	**3983**	**462**	**2176**
Detection & Navigation	1343	133	758	462	5604	3749
Antennas/ Communication	**3380**	**1092**	**1707**	**2716**	**3749**	**23**

UAVs, aircraft detection and navigation, autonomous flight control, sensing and perception, human-UAV interaction, energy-efficient flight, and swarm control. By generating complete virtual replicas that accurately replicate the physical entities in real time, the combination of Digital Twins and AI not only improves the accuracy and efficiency of these systems but also opens up new creative possibilities. This revolutionary strategy has the capacity to drastically alter how technology and automation are used in many different industries.

A. DT AND AI INTEGRATION IN UAV COMMUNICATION

Antennas are an important part of UAV design because they are necessary for signal transmission and reception, which is what makes them function. Antennas for unmanned aerial vehicle (UAV) applications, such as communication, must be small, light, and strong enough to survive in challenging environments [113], [114], [115], [116]. To improve UAV performance, sophisticated technology development has been the main emphasis of recent research on UAV antennas [113], [114], [115], [116], [117], [118]. Along with exploring computational and multi-layered learning approaches for antenna design and optimization [119], [120], [121], researchers are building high-gain, wideband, multibeam antennas and integrating them with other subsystems including power and control systems [115].

B. IoT INTEGRATION WITH UAVS

New opportunities for data gathering, processing, and communication across a range of industries have been made possible by IoT-enabled drones. Combining IoT with UAVs allows a network of connected sensors, devices, and UAVs to collect, process, and share data in real time.

Research on IoT-enabled UAVs has focused mostly on developing scalable and efficient network topologies, data processing algorithms, and communication protocols [121], [122]. They have been deployed for different purposes such that enhanced disaster management and application efficacy and efficiency [123]. For instance, sensor-equipped UAVs can gather information on temperature, soil moisture, and crop health. This information can then be evaluated in real-time to help with fertilization and irrigation schedule decisions. In a similar vein, UAVs can be used to track and evaluate natural catastrophe damage, facilitating a quicker and more precise response. IoT-enabled UAVs have a lot of potential, but there are also a lot of obstacles that need to be overcome. Ensuring the security and privacy of IoT-enabled UAVs is imperative and to create efficient systems for processing and analyzing data. On the other hand, the study of UAV integration with IoT is a promising topic with the potential to revolutionize many other industries and open new applications [124], [125].

C. AIRCRAFT DETECTION & NAVIGATION

It is crucial to guarantee the safe operation of Unmanned Aerial Vehicles (UAVs), especially in shared airspace where accidents involving manned aircraft are a serious risk. The primary responsibility is to identify and avoid these kinds of encounters. The capacity to detect aircraft in real-time is necessary for managing the coexistence of manned and unmanned aircraft. Current developments in the field of UAV aircraft detection focus on building complex systems that can recognize and track aeroplanes. Numerous sensors are used by these systems, including optical cameras, radar, and LIDAR. Even with these advancements, it is still difficult for traditional radar systems to recognize small aircraft, especially those used for general aviation [120], [121], [122]. In order to overcome this obstacle, scientists are exploring the use of multi-layered and computational learning to improve the accuracy and dependability of aircraft detection systems. This novel method aims to improve the ability to distinguish, especially when it comes to smaller and less noticeable aircraft.

Additionally, a crucial aspect of current research is on the smooth integration of aircraft detection systems with UAV navigation and control systems [123], [124], [125]. This synergy has the potential to guarantee the smooth functioning of both manned and unmanned aircraft. By enabling autonomous flight path adaptation in reaction to identified aircraft, such integration improves overall operational safety for unmanned aerial vehicles (UAVs). Beyond safety considerations, research on aircraft detection for unmanned aerial vehicles (UAVs) is critical. It is essential for enabling the broad use of UAV technology in a variety of industries, including delivery, inspection, and surveillance. To ensure the safe and effective integration of UAVs into shared airspace environments, a concentrated research effort is crucial.

D. AUTONOMOUS FLIGHT CONTROL (AFC)

Autonomous flying pertains to the capacity of unmanned aerial vehicles (UAVs) to function without the need for human intervention. Sophisticated control algorithms [80] and navigation systems that allow UAVs to fly, maneuver, and carry out tasks autonomously [80] are used to do this. Autonomous flight is a challenging and complex problem in UAV research that requires the integration of multiple technologies, such as sensors [126], computer vision [127], and artificial intelligence [30]. Unmanned aerial vehicles (UAVs) that can perform complex tasks, such as precision landing, safely and successfully without requiring human aid are the aim [42], [43], [128]. One of the main challenges in autonomous flying is the development of UAVs that can navigate and avoid obstacles in real-time while maintaining stability and control.

This calls for the creation of sophisticated sensors [126] and control algorithms [101] that can precisely recognize and react to environmental changes. Ensuring the safety and dependability of UAVs is a major concern in autonomous flying, especially in situations where human participation is limited or in dangerous locations [102]. Researchers are creating new methods for operating, diagnosing, and monitoring UAVs to overcome these difficulties. Some of these methods include the integration of real-time monitoring systems, backup systems, and failsafe mechanisms. The development of unmanned aerial vehicles (UAVs) that can carry out a wide range of duties safely, effectively, and dependably without the assistance of a person is the aim of autonomous flight.

E. SENSING & PERCEPTION

UAVs rely heavily on their perception and sensing capabilities, which let them gather, process, and analyze environmental data. These characteristics are required for UAVs to perform a range of tasks, including mapping, surveillance, navigation, and inspection. These fields of study, however, are difficult and complex, requiring the fusion of several technologies, such as AI, computer vision, and sensors. The goal is to create unmanned aerial vehicles (UAVs) that can sense and comprehend their surroundings and make decisions based on the facts. One of the key components of perception and sensing is the integration of many sensors, such as cameras, radar, and LiDAR [53], [54]. These sensors give UAVs data about their surroundings, such as the positions of obstacles, other objects, and the terrain. This involves tracking movement, distinguishing objects, and spotting patterns. Furthermore, researchers are looking at the use of reward-based learning algorithms and multi-layered algorithms [128], which would enable UAVs to acquire experience and progressively improve their perception and sensing abilities. The goal of computer vision and sensing in UAVs is to develop systems that can accurately see and interpret their surroundings and make decisions based on that knowledge. Agricultural [98], construction, mining [100], mining [99], maritime applications [39], mining [99], military operations, and search and rescue missions such as remote sensing for wildfires [51], among many other industries, could be revolutionized by this. Additionally, to improve their capabilities, researchers are investigating the possibility of cooperative sensing by employing numerous UAVs [102].

F. HUMAN – UAV INTERACTION

The study of human-UAV interaction is a new area of study that looks at how people engage with UAVs in a variety of settings, including entertainment, education, and research. It might completely transform several sectors. Creating novel interfaces and technologies that allow people to engage with UAVs in creative and natural ways is a key component of human-UAV interaction [62]. These technologies encompass gestures, augmented and virtual reality, and other types of human-machine interaction [63]. One of the main challenges in human-UAV interaction is developing UAVs that can respond to human input in real-time while maintaining stability and control.

This entails the development of fresh, approachable human-machine interfaces in addition to the integration of complex control algorithms and sensors. Another challenge in human-unmanned aerial vehicle interactions is ensuring the safety and reliability of UAVs, particularly in scenarios when human interaction is minimal. There are several approaches that have been proposed for controlling UAVs using hand gestures, body language, and natural language. Intelligent human-UAV interaction systems have been developed, and they recognize gestures and offer efficient UAV control through the use of ML and DL algorithms [63], [64], [65], [66].

Additionally, a few research studies have suggested innovative architectures that let users operate the UAV using their own natural body motions [67], [69]. In addition to technological methods, several studies have looked at human variables and difficulties in using UAVs, like workload, training, and user interfaces [69]. Another important area of research in human–UAV interaction is understanding human decision-making when operating UAVs, especially in search and rescue applications [120]. This emphasizes how crucial it is to create human-UAV interaction systems that are efficient and easy to use in a variety of settings and applications. The latest advancements in human-UAV interaction to date has been reviewed by a scoping review that identified domains such as entertainment, transportation, and public safety, as well as another survey that provided an overview of various control interfaces, gesture recognition techniques, and autonomous operation methods [121].

Additionally, the research has examined the human components and difficulties that come with operating UAVs, such as problems with workload, training, and user interfaces [119]. There is still more research to be done on human decision-making while using UAVs, particularly in search and rescue scenarios [120]. This emphasizes how crucial it is to create user-friendly, effective human-UAV interface technologies that can be applied in a variety of fields.

G. ENERGY EFFICIENT FLIGHT

Energy-efficient flight is a critical area of study for unmanned aerial vehicle researchers in order to build drones that can fly for long stretches of time while consuming the least amount of energy. Energy efficiency must be attained in order to improve UAV performance and capabilities, such as flying duration, cargo capacity, and range. A number of approaches are being investigated by researchers [53], such as incorporating alternative energy sources like solar power [154], lightweight materials, and aerodynamic design optimization [53]. One of the main obstacles to attaining energy-efficient flight for UAVs is weight reduction. Researchers are looking into using lightweight materials like composites and innovative manufacturing processes to lessen the weight of UAVs in order to address this.

In addition, optimizing the propulsion system—which includes developing new propulsion technologies and using more efficient engines—is essential to reaching energy efficiency [105], [106]. Hybrid and electric propulsion systems offer greater energy efficiency than traditional internal combustion engines, and research is being done on merging these technologies. Integrating alternative energy sources, such solar electricity, is another field of study [107], [108]. New lightweight solar panels and durable energy storage devices need to be created to get energy-efficient flight. This opens new uses and applications. Massive data transfers, however, can cause delays and significant energy consumption when used for communication and monitoring.

H. SWARM CONTROL

Within the realm of unmanned aerial vehicles (UAVs), swarm behaviour research tries to investigate the collective behaviour of groups, or "swarms," of UAVs [120], [121]. Potential effects of swarm behaviour on military operations, search and rescue, and environmental monitoring applications have spurred the development of algorithms and control systems that enable UAVs to coordinate their actions and cooperate to accomplish a shared objective. One of the difficulties with swarm behaviour is getting UAVs to work together effectively while adjusting to shifting locations and situations. To address this problem, scientists are developing novel algorithms for cooperation and coordination, as well as for resource management and task distribution [28]. The development of algorithms, including the incorporation of AI methods like reward-based learning and multi layered algorithms, that enable UAVs to operate independently and make decisions based on their environment is another aspect of swarm behaviour [33]. UAV swarms cannot function properly without communication and control architectures [123].

Another crucial component of swarm behaviour is path planning. The most recent advancements in this topic are covered in a recent review [33] of AI applied to path planning in UAV swarms. Another work that looks at the motion planning of UAV swarms, recent difficulties, and options [80] emphasizes the significance of motion planning in swarm behaviour. Furthermore, a strategy for the collaborative motion planning of UAV swarms is proposed in a work on collaborative UAV swarms towards coordination and control mechanisms [126]. Localization in UAV swarms is a significant topic in swarm behaviour that is handled by high-level control of UAV swarms using RSSI-based location estimation [124]. Lastly, swarm behaviour has several uses. For example, the UAV swarm can be used to continuously patrol in unknown locations [30], [127].

In recent years, the field of UAVs has experienced a notable impact from the application of AI. Through AI, UAVs may now operate independently, increasing their effectiveness and efficiency across a range of uses. The application of AI in UAVs has seen some of the most important contributions and studies, such as object identification and tracking [42], [43], [128], [129], [130], planning pathways [33], videos and images processing [43], [130], artificial intelligence for swarms [33], [121], self-navigating systems [92], [131], and counterintelligence [131].

Convolutional neural networks (CNNs) and recurrent neural networks (RNNs) are two examples of AI algorithms that have been employed for farming [8], search and rescue operations [141], and reconnaissance [111]. These algorithms have been used to recognize and track aircraft [43], objects [138], [139], [140], and real-time items from UAVs [11], [132]. With applications in delivery, inspection, and surveillance, AI also makes it possible for UAVs to travel independently in challenging settings, steer clear of obstructions and make decisions in real time using sensor data [30], [42], [43], [80], [96], [97], [98], [99], [100], [101], [102], [103], [104], [105], [106], [107], [108], [109], [110], [111], [112], [113], [114], [115], [116], [117], [118], [119], [120], [121], [122], [123], [124], [125], [126], [127], [128], [129], [130], [131], [132], [138], [139], [140], [141], [142]. Moreover, a swarm of UAVs that can cooperate to accomplish tasks has been created by using AI algorithms to coordinate the movements of multiple UAVs [33], [121]. Applications for this exist in search and rescue, military operations, and surveillance.

Moreover, AI algorithms have been used to evaluate UAV-captured images and videos in order to extract valuable data such as anomaly detection, semantic segmentation, and object recognition. Many sectors, such as catastrophe management, environmental monitoring, and agriculture, can benefit from these skills.

The review paper integrates the potent ideas of control theory and digital twins, which significantly enhances the technology of unmanned aerial vehicles (QUAVs) with quadrotor underactuation. The paper explores novel applications of digital twins in conjunction with control theory, in addition to offering a thorough explanation of basic ideas including the underactuated UAV model and various control strategies. The paper discusses the real-world difficulties that QUAVs encounter in changing environments and proposes innovative methods to improve autonomy and efficiency. Most importantly, it ensures that readers are informed about the most recent developments in the industry by keeping them up to date on recent developments. An innovative concept that could lead to revolutionary developments in autonomous flight control, human-UAV interaction, energy-efficient flight, and swarming UAVs is the integration of digital twins with computer vision, artificial intelligence (AI), sensing and perception, and the internet of things (IoT). The paper goes above and beyond theoretical considerations by offering helpful recommendations for applying control theory and showing how the use of digital twin technology could accelerate control theory's revolutionary potential in QUAV research. Because of its comprehensive approach, the study is positioned as a useful tool for academics looking to further the capabilities of underactuated quadrotor UAVs by finding both theoretical underpinnings and practical insights.

Above mentioned applications of digital twins in UAV control systems are investigated in a simulation environment that is carefully designed to mimic real-world situations, providing a platform for in-depth investigation and testing. Through the use of sophisticated simulation platforms and tools, researchers are able to better understand the dynamic interactions that occur between UAV control systems and digital twins. A strong basis for building and simulating digital twins of UAVs is provided by software programmes like MATLAB/Simulink and ROS (Robot Operating System), which enable the integration of complex control algorithms and sensor models. Furthermore, dynamic and realistic UAV simulations are made possible by platforms like Gazebo and AirSim, which make it easier to assess control tactics in a variety of scenarios. By allowing researchers to test and improve theoretical ideas, validate control algorithms, and evaluate the performance of digital twins under different conditions, these simulation environments advance UAV control systems virtually before moving on to real-world implementations.

VI. CHALLENGES AND CONSTRAINTS

This section provides a critical analysis of the difficulties and limitations associated with control systems and DT-based solutions for quadrotor unmanned aerial vehicles (UAVs), providing a nuanced viewpoint on their effectiveness:

- The quadrotor UAV model, which was developed using the Newton Euler modelling approach, has a gimbal lock/singularity problem and is plagued by differential equations. This method yields a heavily coupled state space model, which is difficult to handle. Researchers find it difficult to develop a non-linear state space model that considers unmodeled dynamic elements and fits the model's complexity with the real-world physical UAV.
- Researchers offer a variety of control strategies to address typical problems such trajectory planning, tracking error minimization, and set-point regulation. But the combination of robust and adaptive control schemes—such as adaptive-robust, robust-adaptive, or robust-robust—raises concerns about how effectively and practically they can address these issues. Because of their lengthy experiment durations, complex controller designs, and sluggish reactions, control techniques like PID and Backstepping are less suitable for time-sensitive applications when temporal inefficiencies are revealed through their implementation.
- Moreover, difficulties arise in ensuring reliable and consistent performance due to uncertainties in gain scheduling simulations and the requirement for continuous tuning in important systems.
- A complicated set of issues arises when AI and DT are integrated into UAV antenna systems for communication, highlighting the necessity of striking a careful balance between advanced computational capabilities and the physical constraints of UAVs, such as weight and size limitations.
- Several of the control algorithms are configuration-sensitive, which impacts the robustness and adaptability of the control system. Because of this sensitivity, it is challenging to keep stability and performance under dynamic circumstances or when system features change. However, some of them have trouble with aggressive gain, overshooting, and chattering effects. Achieving steady and seamless control responses is made more challenging by these occurrences, particularly when there's a possibility that adjusting a parameter could have unforeseen implications.
- The challenges include making designs adaptable to extreme environmental conditions, effectively managing computational complexity, guaranteeing security and dependability, keeping up with the rapid advancement of technology, and bridging the disciplinary boundaries between experts in DT, AI, and antenna design.

The present critical assessment sheds light on the diverse array of obstacles that Quadrotor UAVs must overcome, and it advocates for a thorough and well-thought-out approach to ensure their continuous progress.

VII. FUTURE TRENDS AND DEVELOPMENTS

Within the dynamic field of unmanned aerial vehicles (UAVs), the combination of Artificial Intelligence (AI) and Digital Twins has unveiled a world of game-changing opportunities. Critical sectors such UAV communication, IoT integration with UAVs, aircraft detection and navigation, autonomous flight control, sensing and perception, human-UAV interaction, energy-efficient flying, and swarm control have all been affected by the seamless integration of these technologies. This synergy creates virtual representations of physical entities in real time, which improves accuracy, productivity, and creative potential. Researchers are at the forefront of examining the many uses of this innovative method and tackling the related issues as it continues to reshape technology and automation paradigms across a variety of industries.

In terms of the future, there are a variety of interesting paths that scholars in this discipline could pursue. It is recommended that researchers focus on improving UAV communication, developing machine learning (ML) and deep learning (DL) techniques, and investigating these areas in order to optimize antenna design. Furthermore, the Internet of Things (IoT) and UAV integration offer chances to improve data collection and processing, which calls for the creation of effective network designs and communication protocols. Researchers are pushed to push the limits of unmanned aerial vehicles (UAVs) in the field of autonomous flight control by improving control algorithms, propulsion systems, and investigating alternate energy sources for energy-efficient flight.

The complexities of human-UAV contact also necessitate further research into cutting-edge interfaces, intuitive human-machine interactions, and security and privacy issues. The development of algorithms for efficient UAV collaboration and the resolution of problems with resource management, task distribution, and communication structures should be the main goals of swarm control research. All things considered, there will be plenty of chances for innovation and discoveries that will advance UAV technology in the future for academics working in this field.

VIII. CONCLUSION

The use of artificial intelligence (AI) and digital twins in the unmanned aerial vehicle (UAV) industry has sparked a revolution that is having an impact on several critical areas, such as UAV communication, IoT integration, aircraft identification, autonomous flight control, and more. This harmonious mix opens hitherto untapped creative possibilities and enhances accuracy and efficiency by instantaneously creating virtual duplicates of real-world things. Scholars are at the forefront of investigating and addressing problems in this new paradigm that is revolutionizing technology and automation across multiple industries. There are tons of exciting prospects in this field for researchers in the future. Enhancing UAV communication, examining IoT integration with UAVs, and improving antenna design using multi-layered and computational algorithms are few of the main areas of attention. Researchers are asked to investigate novel approaches to autonomous flight control, such as propulsion technologies, more effective control algorithms, and sustainable energy sources. Human-UAV interaction is a complicated topic that requires ongoing research into novel interfaces, intuitive HMIs, and trustworthy security and privacy solutions. However, communication is the primary problem that UAVs are now experiencing. The development of microprocessors, which will enable the intelligent, autonomous operation of a range of devices, can overcome this problem. The cost-effectiveness, independence and remote operations, speedy data transfer, variable network performance, flight range, and dynamic node mobility and topology are just a few of the features that make drones unique. It is evident that academics have categorized the unresolved UAV issues into multiple groups. Technology, safety, privacy, security, and legal considerations are all covered in these themes. It is prudent to consider the potential for relationships between these categories, since some study paths have the ability to impact several categories at once.

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