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Review

A Survey: Future Smart Cities Based on Advance Control of Unmanned Aerial Vehicles (UAVs)

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Abstract: This article presents a survey of unmanned aerial vehicle (UAV) applications in smart cities, emphasizing integration challenges. Smart cities leverage innovative technologies, including the Internet of Things (IoT) and UAVs, to enhance residents' quality of life. The study highlights UAV applications, challenges, limitations, and future perspectives of smart city development. Advanced control methods for maximizing UAV benefits are discussed. Control theory challenges and issues for the deployment of UAVs are addressed. By concentrating on challenges, potential applications, and advanced control techniques, this paper offers insights into UAVs' role in shaping the future of smart cities.

Keywords: future smart cities; internet of things; unmanned aerial vehicle applications; optimization methods; challenges

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1. Introduction

To define the scope of the survey article, the research question or objective that the survey aims to address and the methodology are outlined in Figure 1. Optimizing age and power consumption in Internet of Things (IoT) applications using unmanned aerial vehicles (UAVs) and their battery recharge is a crucial undertaking for the development of future smart cities [1]. Optimizing the flight paths of UAVs to minimize age and power consumption, while ensuring comprehensive data coverage, holds significant importance. Leveraging UAVs for environmental monitoring presents both challenges and opportunities, particularly in collecting data from remote or inaccessible regions. The effectiveness of UAV systems has been exemplified through various case studies, showcasing their potential impact [2]. Efficient control of UAVs plays a crucial role in the betterment of smart cities. UAVs equipped with advanced control systems can efficiently navigate through urban environments, collecting high-quality data from various sensors. This data is invaluable for smart city applications, such as traffic management, environmental monitoring, and infrastructure assessment. By controlling UAVs effectively, cities can gather accurate and real-time information, enabling informed decision-making and proactive interventions [3,4]. UAVs with efficient control algorithms can optimize the use of available resources in smart cities. For instance, they can monitor utility networks, detect leakages or faults, and assist in maintenance activities. By identifying inefficiencies and potential problems promptly, cities can improve the reliability and sustainability of critical infrastructure systems like water supply, electricity grids, and waste management. UAVs with precise control capabilities can be deployed for surveillance and security purposes in smart cities. They can monitor crowded areas, identify suspicious activities, and provide real-time situational awareness to law enforcement agencies [5]. With efficient control, UAVs can navigate complex urban environments, maintain stable flight paths, and quickly respond to emerging security threats. During emergencies such as natural disasters or accidents, UAVs with efficient control systems can be deployed for rapid response and rescue operations. They can quickly reach inaccessible or hazardous areas, assess the situation, and provide critical information to emergency responders. By streamlining rescue efforts and improving coordination, efficient control of UAVs can save lives and minimize damage in smart cities. UAVs can play a significant role in improving transportation systems within smart cities. With efficient control algorithms, they can support traffic management, monitor congestion, and provide real-time data for route optimization. UAVs can also facilitate last-mile delivery services, reducing traffic congestion and enhancing efficiency in urban logistics [6].

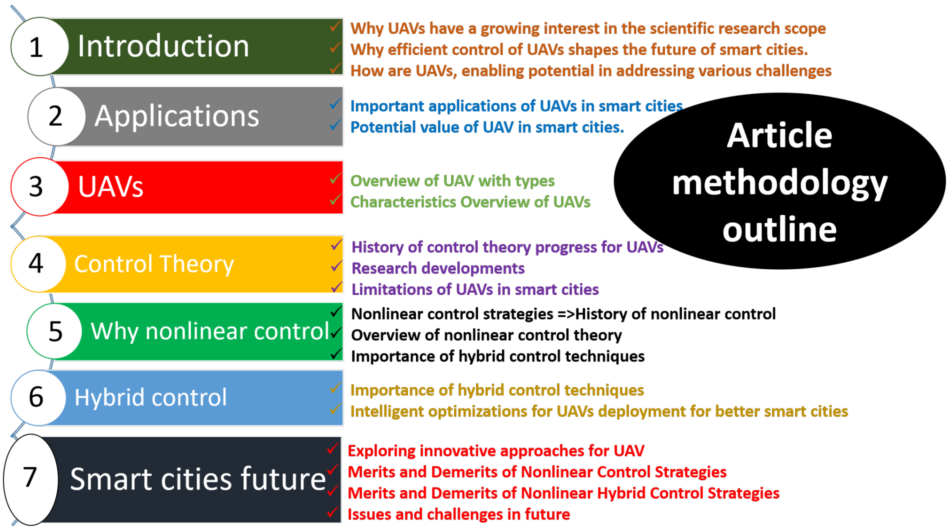

Figure 1. Overview of article outline.

UAVs have emerged as a highly significant technology in the geoscience and remote sensing fields over the past twenty years. They have gained popularity across various applications and have often replaced other platforms due to their versatility and relatively affordable costs. This rise in prominence is evident from the substantial number of scientific papers dedicated to UAVs published across different research communities during this period. According to Scopus, more than 80,000 papers have been published since 2001 using terms like "UAV", "drone", "UAS", and "RPAS" in the title or keywords (Figure 2). The majority of these publications are within the engineering and computer science domains [7]. This growing interest in UAVs from the scientific community is not limited to a single citation indexing database, as other databases also reflect this trend. Furthermore, the UAV business has experienced significant financial growth, with a valuation of several billion dollars per year. Although the majority of the market is currently focused on military applications, the future prospects for UAVs are promising. Economic interests, technological advancements, the miniaturization of onboard sensors, and the development of new algorithms and software have collectively driven the emergence of new applications, which in turn have created new business opportunities. While UAV surveying applications were the initial focus, more advanced applications have emerged, leading to new requirements and further expanding the scope of UAV utilization. Notably, UAV systems capable of rapid, automated, and autonomous geospatial data collection are making significant contributions to the ongoing fourth industrial revolution [8]. Indeed, new and emerging applications of UAVs continue to expand across various industries. Construction and infrastructure monitoring are prime examples of how UAVs are being utilized for aerial inspections, progress tracking, and site surveillance in construction projects. They offer efficient and cost-effective means of obtaining high-resolution imagery, collecting data, and monitoring project developments.

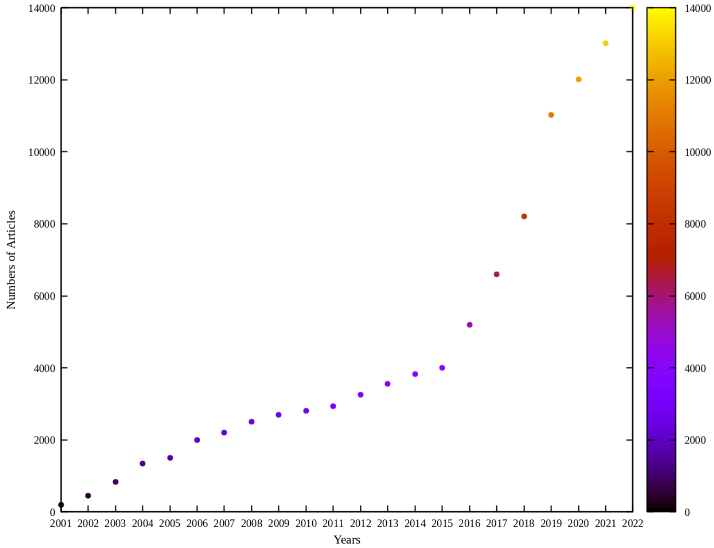

Figure 2. Scientific research articles according to SCOPUS [6].

Control theory (nonlinear, linear, intelligent control, and hybrid control) is important for UAVs in smart cities. UAVs, or drones, play a crucial role in various applications within smart cities, such as surveillance, delivery services, and infrastructure inspection. Control theory provides the foundation for designing and implementing control algorithms that enable UAVs to navigate, stabilize, and perform tasks autonomously.

In smart cities, UAVs need to operate in complex and dynamic environments, where they must adapt to changing conditions and interact with other systems. Control theory helps in developing control strategies that allow UAVs to respond to environmental changes, avoid obstacles, optimize energy consumption, and ensure safe and efficient operations. Efficient control is essential for UAVs in smart cities as it enables them to operate autonomously, adapt to changing conditions, and perform tasks with precision and efficiency. This review article focuses on the contribution of efficient UAV control in optimizing age and power consumption in IoT applications. Below, you will find a comprehensive analysis based on the literature of the proposed research, highlighting key ideas for promoting the future of smart cities based on control actions of a controller:

- Control theory serves as the cornerstone for designing stable and agile flight control algorithms, ensuring safe operations in bustling urban areas prone to obstacles and unpredictable weather [9]. Smart cities demand highly autonomous UAVs for efficient task execution. Control theory enables the creation of advanced navigation systems, allowing UAVs to navigate complex urban environments autonomously, evade obstacles, and dynamically adjust flight paths [10]. In smart city applications, UAVs often carry specialized payloads and sensors for tasks like surveillance and environmental monitoring. Control theory optimizes UAV motion and sensor coordination, enhancing data accuracy and critical information capture [11].
- Smart cities emphasize sustainability and energy conservation. Control theory aids in optimizing UAV flight trajectories and power management, thereby increasing energy efficiency and extending flight endurance.
- Future smart cities might see the deployment of UAV swarms for collaborative tasks. Control theory enables swarm coordination, ensuring efficient communication, formation control, and the achievement of collective goals [12].
- As the number of UAVs in urban airspace increases, effective traffic management becomes essential to prevent collisions and congestion. Control theory is fundamental

to designing collision avoidance and traffic coordination algorithms for safe and efficient UAV operations [13].

- In times of emergencies or natural disasters, UAVs can be deployed for search and rescue missions, damage assessment, and communication support. Control theory plays a pivotal role in optimizing UAV behavior in dynamic and challenging environments [14].
- Integrating UAVs into smart cities requires adherence to aviation regulations and safety standards. Control theory contributes to developing UAV control systems that comply with these regulations, ensuring responsible and lawful operations [15].
- Smart cities are dynamic environments with constantly changing conditions. Control theory enables UAVs to adapt and respond in real-time to changing environmental factors, enhancing their reliability and effectiveness [16].

Its application ensures the safe, efficient, and reliable operation of UAVs, enabling them to fulfill their potential in transforming urban landscapes and addressing various challenges for a smarter, more sustainable future.

2. Important Applications of UAVs in Smart Cities

UAV infrastructure in smart cities provides a cost-effective and efficient means of data collection, monitoring, surveillance, and infrastructure assessment. They contribute to better urban planning, resource management, emergency response, public safety, and sustainable development, ultimately improving the quality of life for city residents represented in Figure 3.

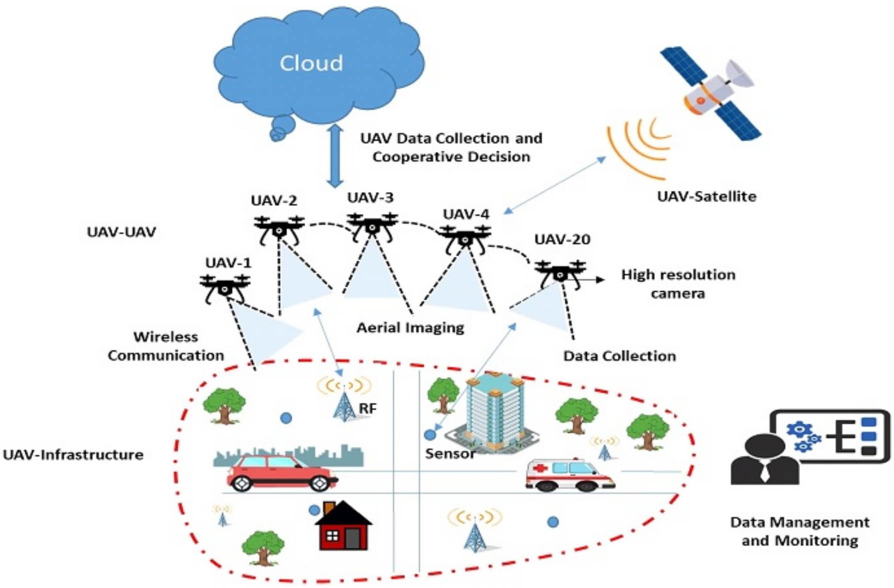

Figure 3. Infrastructure of UAV for smart cities [16].

UAVs equipped with sensors, cameras, or other data collection devices can capture high-resolution imagery, perform aerial surveys, and collect various types of data. This data is invaluable for urban planning, infrastructure management, environmental monitoring, and decision-making processes in smart cities. UAVs enable efficient and cost-effective data collection, providing accurate and up-to-date information. Drones can inspect critical infrastructure, such as bridges, buildings, power lines, and pipelines. They can reach inaccessible or hazardous areas, allowing for quick and accurate assessment of structural integrity, identification of maintenance needs, and detection of damage or potential risks. Regular inspections using UAVs enhance safety, reduce maintenance costs, and improve the lifespan of infrastructure. Drones are valuable tools in emergency situations. They can be quickly deployed to assess disaster-affected areas, search for missing persons, and provide situational awareness to emergency responders. UAVs equipped with thermal sensors can detect hotspots in fires or identify people in need of rescue. Additionally, they can deliver emergency supplies to remote or inaccessible locations, improving response times and saving lives. UAVs enable efficient monitoring of environmental parameters such as air quality, pollution levels, temperature, and vegetation health. This data aids in identifying environmental challenges, assessing the impact of urban activities, and implementing sustainable solutions. UAVs can support environmental planning, pollution control, and conservation efforts in smart cities. Delivery drones offer an efficient and environmentally friendly alternative for transporting goods within smart cities [17,18]. They can navigate congested areas more easily and reach destinations faster, enabling quick and convenient delivery of packages, medical supplies, or emergency response materials. Delivery drones contribute to reducing traffic congestion, lowering carbon emissions, and enhancing logistics operations.

The advancements in electronics and manufacturing processes have allowed for the miniaturization of controllers, sensors, and processors while retaining their effectiveness. This breakthrough has given rise to compact configurations of UAVs. The potential inherent in this size reduction is vast and offers numerous advantages. In 2016, PwC published the report "Clarity from Above", revealing that the addressable market value of drone-powered solutions exceeds USD 127 billion, indicating that the drone revolution is causing significant disruptions across a wide range of industries [19]. Figure 4 provides a schematic representation of the estimated value for some key industries. UAVs, commonly known as drones, have a wide range of applications across various fields due to their versatility, efficiency, and ability to access hard-to-reach areas. Here are some of the key applications of UAVs in different sectors:

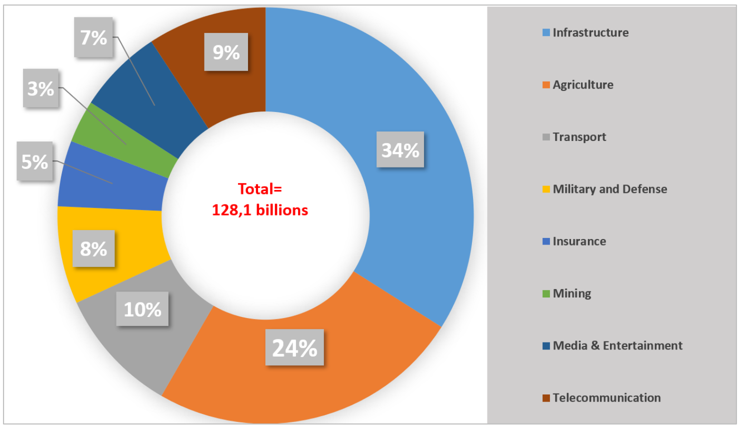

Figure 4. Potential value of UAV-based solutions in key industries for global market [20].

2.1. Agriculture

Drones are used for precision agriculture. They can monitor crop health, track livestock, and even assist in planting and spraying crops. They can provide detailed aerial imagery that helps farmers make informed decisions about their crops and livestock [21].

2.2. Construction and Infrastructure

Drones are used for surveying land, inspecting structures, and monitoring construction progress. They can provide high-resolution images and videos that can help in planning, monitoring, and inspecting construction sites [20].

2.3. Disaster Management

Drones can be used in disaster management for search and rescue operations, damage assessment, and delivering emergency supplies. They can reach areas that are difficult or dangerous for humans to access [22].

2.4. Environmental Monitoring and Conservation

Drones are used for wildlife monitoring, forest conservation, and environmental research. They can collect data on wildlife populations, track animal movements, and monitor environmental changes [23].

2.5. Delivery Services

Companies like Amazon and Google are testing drones for delivering goods to customers. Drones can potentially make deliveries faster and more efficient, especially in congested urban areas [24].

2.6. Media and Entertainment

Drones are used for aerial photography and videography in films, news coverage, and sports events. They can capture unique angles and perspectives that would be difficult or impossible to achieve with traditional cameras [25].

2.7. Military and Defense

Drones are used for surveillance, reconnaissance, and combat missions. They can gather intelligence, carry out strikes, and perform other tasks without putting human lives at risk [26].

2.8. Healthcare

Drones are being explored for transporting medical supplies, especially to remote or hard-to-reach areas. They can deliver medicines, vaccines, blood samples, and other medical supplies quickly and efficiently [27].

2.9. Scientific Research

Drones are used in various scientific research fields, including meteorology, geology, and archaeology. They can collect data in hazardous or inaccessible areas, making them a valuable tool for researchers [28].

2.10. Real Estate

Drones are used in the real estate industry to capture aerial views of properties. This provides potential buyers with a better perspective of the property, its surroundings, and features like the roof that is difficult to inspect from the ground [29].

Understanding the types and characteristics of UAVs is essential for comprehending their capabilities and operation means that in order to fully grasp what UAVs are capable of doing and how they function, it is crucial to have knowledge about their specific qualities and physical makeup.

3. Types and Characteristics of UAVs

Different types of UAVs are important for various applications due to their unique capabilities and features. The choice of any particular drone depends on the purpose of such a drone. Studying the types of UAVs regarding their structure is important for understanding their applications in society. The structure of a UAV can greatly impact its capabilities, performance, and suitability for different tasks [28]. Different types of UAVs have varying designs, such as fixed-wing, rotary-wing (e.g., helicopters), and hybrid configurations as mentioned in Figure 5. Each type has its own advantages and limitations, making them suitable for specific applications. For example, fixed-wing UAVs are known for their long endurance and high-speed capabilities, making them suitable for tasks such as aerial mapping, surveillance, and cargo delivery over long distances. Rotary-wing UAVs, on the other hand, offer vertical takeoff and landing capabilities, making them ideal for tasks that require hovering, maneuverability, and close-range operations, such as aerial photography, search and rescue, and inspection of infrastructure [30].

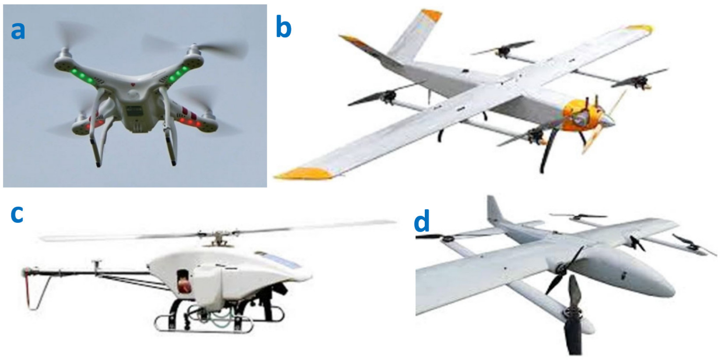

Figure 5. Types of UAV rotors: (**a**) Rotary Wing (Multicopter), (**b**) Fixed-Wing, (**c**) Rotary Wing, (**d**) Fixed-Wing [29].

By studying the structure of UAVs, researchers, and engineers can better understand the capabilities and limitations of different types of UAVs, enabling them to design and develop UAVs that are optimized for specific applications. This knowledge is crucial for advancing the field of UAV technology and maximizing their potential benefits in various sectors, including agriculture, transportation, environmental monitoring, disaster management, and more. A short overview of UAVs based on their types is provided in Table 1. It is important to note that UAV technology continues to evolve rapidly, and new features and characteristics are constantly being developed and integrated into these systems. UAVs are typically operated and controlled by a remote pilot on the ground or can even operate autonomously using pre-programmed flight paths [31]. The remote pilot uses a control station to maneuver the drone and make decisions regarding its flight. UAVs do not carry any human pilots onboard, which makes them autonomous and capable of operating in environments that may be dangerous or inaccessible for manned aircraft. Studying the types of UAVs regarding their characteristics is highly important for understanding their capabilities, limitations, and applications. The characteristics of UAVs encompass various aspects that influence their performance, functionality, and suitability for specific tasks [32]. By taking concentration on the characteristics of UAVs, researchers, engineers, and operators can make informed decisions about which type of UAV is best suited for a particular application. This knowledge helps optimize UAV selection, design, and operation, leading to more efficient and effective use of UAV technology in various industries, including agriculture, construction, environmental monitoring, and public safety [33]. The characteristics of UAVs are elaborated in Table 2.

Table 1. Overview of UAV with types [29].

UAV Type	Applications	Advantages	Drawbacks
• Rotary Wing (multicopter) (a)	• photography • filmography • inspection	• hovering • availability • low price	• short flight time • small payload
• Fixed-Wing Hybrid VTOL (b)	• structural inspection • area survey • supply drops	• large area coverage • long endurance • hovering • large payload • great maneuverability • ease of use • efficient camera control • vertical takeoff and landing (VTOL)	• stability issues in wind

Table 1. *Cont.*

UAV Type	Applications	Advantages	Drawbacks
• Rotary Wing (helicopter) (c)	• supply drops • inspection	• hovering • large payload • great maneuverability • ease of use • efficient camera control • vertical takeoff and landing (VTOL)	• high price • short flight time • low stability in wind • dangerous
• Fixed-Wing (d)	• structural inspection • area survey	• large area coverage • long endurance • high speed • great stability • safer recovery from motor power loss	• launching • landing • high price • no VTOL/hover • challenging to fly • training is needed • less efficient for area mapping

Table 2. Characteristics overview of UAVs [33].

Characteristics	Fixed Wing	Rotary Wing	Hybrid
Energy efficiency	High	Low	High
Flight system	Complicated	Simple	Complicated
Landing	Conventional	Vertical	Vertical
Autonomy	No	Yes	Yes
Hovering	No	Yes	Yes
Power supply	Battery, fuel	Battery	Battery, fuel
Endurance	60–3000 m	6–180 m	180–480 m
Payload	1000 kg	50 kg	10 kg
Weight	0.1–400,000 kg	0.01–100 kg	1.5–65 kg

Controlling UAVs using nonlinear control strategies can be highly important and beneficial in certain situations. Nonlinear control approaches offer advantages over traditional linear control methods by accounting for the nonlinear dynamics and uncertainties present in UAV systems.

4. Control Theory Progress for UAVs

The availability of low-cost inertial measurement units (IMUs) has enabled the development of various miniature UAVs. One of the most recent and interesting UAVs is the twin-rotor MIMO system (TRMS), which is capable of vertical takeoff and landing (VTOL). UAV systems have a hovering capability that makes them superior to fixed-wing systems, which cannot hover and are unsuitable for environments that require stationary or quasi-stationary flights. UAV systems have extensive military and civil applications and have attracted significant funding and research interest from various communities. In the last decade, several researchers have completed projects on UAVs. These systems have found utility in a wide range of applications including surveillance, aerial photography, building exploration, climate forecasting, bridge inspection, 3D mapping, swarm missions, and numerous other use cases [19,34].

UAVs have become increasingly important in a variety of control applications due to their flexibility, mobility, and ability to operate in remote or hazardous environments. UAVs have versatile applications, encompassing surveillance, search and rescue operations, inspection tasks, mapping initiatives, agricultural practices, and delivery services. UAVs are also useful in industrial control applications, such as monitoring and controlling chemical plants or power generation facilities [35,36]. One of the main advantages of UAVs for control applications is their ability to provide real-time data and feedback. UAVs can be equipped with a variety of sensors, including cameras, thermal imagers, LiDAR, and gas sensors, among others, that can provide data on temperature, pressure, air quality, and other environmental variables. This data can be used for control applications, such as monitoring the progress of a search and rescue mission, detecting gas leaks in a chemical plant, or assessing the health of crops in an agricultural field [37].

One important benefit of nonlinear UAVs is their ability to operate in complex, dynamic environments. Nonlinear control algorithms can help UAVs adapt to changing conditions and respond quickly to unexpected disturbances, allowing them to navigate through cluttered or congested environments, avoid obstacles, and track moving targets with greater precision [38]. This adaptability and agility are particularly important in modern warfare scenarios, such as the conflict in Ukraine, where UAVs have played an increasingly prominent role. In Ukraine, both sides have deployed a range of UAVs for surveillance, reconnaissance, and attack missions, and these vehicles have demonstrated their effectiveness in gathering intelligence, targeting enemy positions, and disrupting enemy operations [39]. Nonlinear UAVs offer several advantages in this context, including their ability to operate in GPS-denied or jammed environments, their resistance to detection and interception, and their ability to perform complex maneuvers and fly at high speeds with greater stability and accuracy. Overall, the importance of nonlinearities in UAVs reflects the growing importance of these vehicles in modern warfare and the need for advanced control and navigation systems that can help them operate effectively in complex and unpredictable environments [40].

A helicopter is an aircraft that is lifted and moved by one or more rotors, which are typically arranged in an even number. The key advantage of a helicopter lies in its capability to control lift and direction by modulating the rotor speed using motors. This makes helicopters particularly useful in congested or remote areas where fixed-wing aircraft are unable to take off or land. In order for the closed-loop system to achieve the desired response, it must manipulate the controlling variables through control action. The experimental setup for a prototype helicopter involves various components and instruments that are used to test and evaluate the performance, stability, control, and other characteristics of the UAV [38,41]. To model this coupling effect, the dynamics of the UAV must be represented using a set of equations that capture the interactions between the different degrees of freedom. These equations typically include terms that describe the forces and moments acting on the UAV as a result of its motion through the air, as well as terms that capture the effects of the rotor dynamics and control inputs [41]. The UAV setup described above is a system with limited degrees of freedom that is highly nonlinear in nature. It consists of two primary components: a mechanical component (consisting of the main rotor and tail rotor) and an electrical component (comprised of DC motors for both rotors). The mechanical component, which is susceptible to various perturbations, is the primary focus. The main rotor, which controls pitch angle, allows for motion along the vertical axis (in the vertical plane), while the tail rotor, which controls yaw angle, enables motion along the horizontal axis (in the horizontal plane). To regulate the UAV in the presence of coupling effects, a linear controller is implemented, complete with all of its requisite attributes, as expressed in the system's equations [23,41].

Variable structure systems (VSSs) have long piqued the interest of the control engineering community because of their significant nonlinear behavior, dynamical changes over time, coupling influences, and susceptibility to parametric disturbances when treated as controllers. Due to matched and mismatched disturbances, controlling unmanned aerial vehicles (UAVs) can be particularly difficult, and Table 3 represents the challenges and tasks of our research. These technologies are interesting because regular security services and security missions increasingly utilize them in a variety of contexts [42]. TRMS is a class of UAVs that have drawn interest because of their capacity to hover, take off, and land in unexpected places, as well as tilt their angle of flight. Control researchers must overcome the strong coupling, nonlinear dynamics, ambiguities, and gyroscopic torque of UAVs. Applications for these systems are growing in a variety of sectors [35,42]. Rotor rotation, the linkage between rotors, fluctuating propeller rotation speed, susceptibility to parametric perturbations, and the time-varying character of the system are the key difficulties in UAVs [43]. Comprehensive details regarding nonlinear control theory for UAVs are provided in Table 4.

Table 3. Research developments.

Year	Development History
2015	Collision avoidance strategies covered in the article include sensing, tracking, and collision avoidance [44].
2016	Focuses on surveying articles published from 2000 to 2015 that discuss the civil applications of UAVs [45].
2017	Open-source flight controllers that are specifically designed for research purposes [46].
2018	Cellular communication for UAVs. The research aims to bridge the existing gap between the current state of 3GPP regulations and the need for further investigation in this field [47].
2019	The deployment of UAVs within cellular networks [48]. UAV applications, highlighting their benefits, potential challenges, major tradeoffs, and the mathematical tools involved [49]. The utilization of UAVs in the context of 5G/B5G wireless communication [50]. The integration of UAVs in millimeter-wave (mm-wave) communication [51].
2020	The applications of UAVs and the associated challenges, regulations, and future research aspects related to future research in the field of UAV technology [52]. The exploration of software-defined network (SDN) and network function virtualization (NFV) technologies [53]. Study on UAVs from three distinct perspectives: swarms, sensors, and communications [54]. Explore various application scenarios of multi-UAV systems and operating multi-UAV systems and offers insights into addressing these challenges [55,56].
2021	A comprehensive survey of green UAV communications [57]. The development of UAV prototypes and discusses experimental demonstrations that showcase their capabilities [58]. Deep learning tools for detecting vehicles using aerial images captured by UAVs [59].
2022	The study centers around optimization algorithms, such as chicken swarm optimization clustering, bee optimization algorithm, and genetic algorithm [60]. Surveys different task assignment algorithms and examines their main ideas, benefits, drawbacks, and operational features [61].
Current year	In the current year, this study aims to serve as a valuable resource for the research community. It provides researchers with guidelines and motivations to contribute to the advancement of UAV technology. Nonlinear control techniques are essential for UAVs operating in smart cities due to their ability to handle complex dynamics, enhance stability and robustness, optimize control performance, deal with nonlinear sensors and actuators, enable trajectory planning and obstacle avoidance, as well as facilitate fault detection and fault tolerant control. These techniques contribute to the safe, efficient, and reliable operation of UAVs in the urban environment.

Table 4. Overview of nonlinear control theory.

Year	Work	Short Overview
1880s–90s	Poincare	In celestial mechanics, nonlinear dynamics is studied as an n-body problem—limit cycle concept and bifurcation theory [62]
1892	Lyapunov	Analysis of dynamic systems' stability [63]
1910s	Duffing	Using second order nonlinear differential equations to model a dynamic chaotic system Equation [64]
1920s	Van der Pol	Research on limit cycles and oscillator dynamics [65]
1930s	Bode	Frequency response asymptotic representation [66]
1930s	Krylov and Bogoliubov	Invariant measures theorem [67]—elaborate the theory of function method
1932	Nyquist	Regeneration theory [68]
1944	Luré	Abolsute stability problem [69]
1950s	Emelyanov	Theory of variable structure system with sliding mode control [70]
1960	Start	of modern era for nonlinear control
1960s	Edward Norton Lorenz	Chaos theory [71]—butterfly effect [72]
1960	Kalman and Bertram	Review Lyapunov's theory [73]
1961	Popov	Asymptotic stability [74]—hyperstability
1962	Yakubovich	Correlation of two theories results (Luré, Popov's) [75]
1970	Various scientists	Study energy mechanism of dynamic systems [76]
1971	Luenberger	Concept and construction of state observer [77]

Table 4. *Cont.*

Year	Work	Short Overview
1972	Willems Jan	Theory for dissipative systems [78]
1978	Richalet et al.	Model predictive heuristic control [79]
1980s	Zames	Formulation of H control [80]
1989	Ortega and Spong	Concept of passivity-based control (PBC) [81]
1990	Start	of 'activation process'
1990s	Sontag and Wang	Theory of stability [82]
1995	Isidori	Geometric control theory [83]

It is worth noting that ongoing advancements in UAV technology, such as improved battery technology, regulatory developments, sensor capabilities, and cybersecurity measures, aim to mitigate these limitations and enhance the overall effectiveness and reliability of UAV systems as represented in Figure 6.

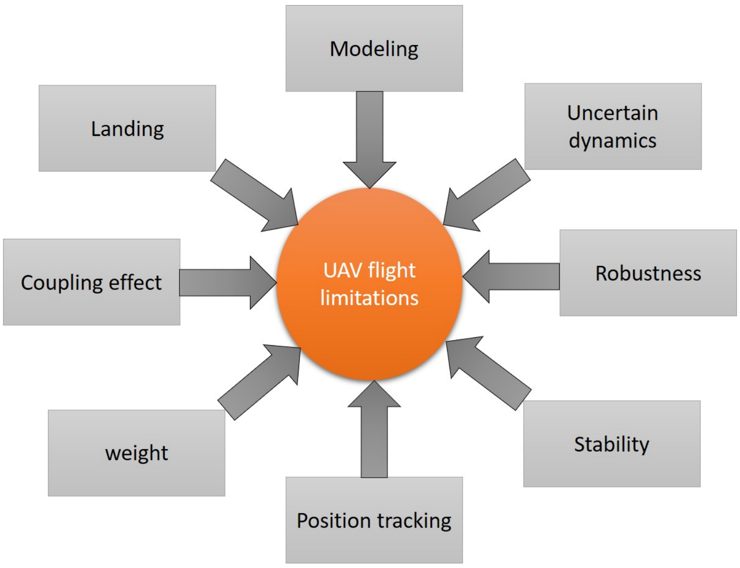

Figure 6. Limitations of UAV in smart cities.

5. Why Nonlinear Control Strategies

Nonlinear control plays a crucial role in the operation of unmanned aerial vehicles (UAVs) in smart cities. Here are some reasons why nonlinear control is important for UAVs in smart cities:

- Handling Complex Dynamics: UAVs are highly maneuverable and can perform various tasks such as surveillance, package delivery, and infrastructure inspection. The dynamics of UAVs are inherently nonlinear due to factors like aerodynamics, wind disturbances, and changing payload weights. Nonlinear control techniques allow for more accurate modeling and control of these complex dynamics, enabling precise and efficient UAV operation [84].
- Enhancing Stability and Robustness: Nonlinear control methods can provide stability and robustness to UAVs operating in smart cities. UAVs need to maintain stability under different operating conditions, including varying wind patterns and sudden disturbances. Nonlinear control techniques such as adaptive control and robust control can effectively handle these uncertainties, ensuring stable flight and reliable performance [85].
- Optimizing Control Performance: Smart cities often require UAVs to perform tasks with specific performance objectives. Nonlinear control techniques enable the optimization of control performance by considering factors like energy efficiency, response

time, trajectory tracking, and obstacle avoidance. Adaptive control algorithms can adapt to changing conditions and optimize control parameters in real-time, maximizing the UAV's efficiency and effectiveness [61].
- Dealing with Nonlinear Sensors and Actuators: UAVs rely on sensors for perception and actuation devices for control. Nonlinear control methods can effectively handle the nonlinearities associated with sensors and actuators. This allows for accurate sensor fusion, sensor calibration, and precise actuation, leading to improved reliability and performance of UAV systems in smart cities [61,84].
- Trajectory Planning and Obstacle Avoidance: UAVs operating in smart cities must navigate complex urban environments while avoiding obstacles and adhering to regulations. Nonlinear control techniques can be used in trajectory planning and obstacle avoidance algorithms to generate feasible and collision-free paths. By accounting for the nonlinear dynamics of UAVs and the surrounding environment, these methods enable safe and efficient navigation in smart city environments [85].
- Fault Detection and Fault-Tolerant Control: In the event of component failures or malfunctions, UAVs need to maintain their control and operation to ensure safety and reliability. Nonlinear control techniques can be utilized for fault detection and fault-tolerant control, enabling UAVs to identify anomalies, adapt their control strategy, and continue operation in a degraded mode. This enhances the resilience of UAV systems in smart cities [86].

5.1. History of Nonlinear Control

The centrifugal "flyball" governor, which was created in the 18th century to manage steam engines by regulating the steam admittance to the cylinder, is the precursor to nonlinear control. But at that time, the governor did not use any particular analytic ideas [36]. Russian mathematician A.M. Lyapunov developed two techniques in 1892 for assessing the stability of dynamic systems given by ordinary differential equations (ODE). The second approach, often known as the Lyapunov direct method, enables stability analysis of nonlinear control systems without the requirement to solve the ODE directly, opening up a wide range of potential applications [87].

According to Lyapunov, the genuine nonlinear system will likewise be stable in a specific area around an equilibrium point if the linear approximation of the system is stable there. His writings were translated into French in 1907, and Kalman and Bertram later rediscovered them in relation to control. Van der Pol's study of electronic oscillations and Duffing's findings on nonlinear vibration both made significant contributions to nonlinear control. Several methods were created to comprehend and forecast diverse phenomena displayed by nonlinear systems, building on the presented nonlinear second-order equations. Subharmonic oscillations, limit cycles, jump phenomena, and frequency entrainment are a few examples of these phenomena. The scientific community did not start tackling the problem of controlling servomechanisms until the late 1930s, when the field of control engineering was still in its infancy [88]. The phase plane method developed by Poincaré was used to analyse these mechanisms, which were roughly represented by second-order systems. Research on nonlinear control of servomechanisms advanced significantly with the outbreak of World War II. Intensified investigations were spurred by the functional requirements put forth by fire-control systems and the operation of guided vehicles. The description function, the phase plane method, and other methods utilizing relay systems were the three main analytical techniques used between 1940 and 1960 for the analysis of nonlinear systems. In the classical era, linear, finite-dimensional, time-invariant systems with single inputs and outputs were used to solve the majority of issues.

The year 1960 marked the beginning of the modern era for nonlinear control [78]. Additionally, the inaugural IFAC (International Federation of Automatic Control) convention was taking place in Moscow at the same time. This invention helped modern control theory to emerge by bringing the theories of physics and Nyquist–Bode feedback closer together. Applications in this era were primarily driven by the space race and the defense industry. Numerous industrial sectors, including those producing cars, ships, steel, paper, and minerals, also used nonlinear control. Due to their nonlinear, time-varying, high-dimensional, poorly modeled, and multivariable nature, the encountered real systems presented difficulties and were outside the scope of classical control theory. The development of digital computers began as a design tool and eventually evolved into a crucial part of control systems. Scientists used the Lyapunov theory in the early 1970s to investigate how the ideas of energy and dissipation relate to one another. They found that dynamic systems might be seen as energy transformational mechanisms. Jan Willems developed a hypothesis for dissipative systems based on this concept [78].

Sontag and Wang developed the notion of input-to-state stability for nonlinear control systems throughout the 1990s [82]. This theory makes it possible to analyze the stability of complex structures using the actions of simple subsystems. Applications in biological and chemical processes have been successful [89]. Isidori introduced the idea of zero dynamics to geometric control theory in 1995 [83]. This theory examines controllability and observability in nonlinear control systems using differential geometry, demonstrating tremendous potential in this area.

Reviewing the early history of nonlinear control critically reveals that the descriptive ideas of optimality, stability, and uncertainty predominated. The introduction of the "activation process", however, during the 1990s resulted in a substantial shift. During this decade, descriptive research underwent a metamorphosis into formal design methodologies through constructive techniques [90]. As a result, attention turned away from merely descriptive methods and towards the creation of systematic, usable methods for creating nonlinear control systems. Table 3, provides a prominent historical advance in nonlinear control theory. In recent years, there have been significant advancements in the research of nonlinear control strategies, leading to a deeper understanding and improved application of these techniques. One noteworthy development is the utilization of modern mathematical tools, such as nonlinear system analysis, to analyze and design control algorithms for complex nonlinear systems. These tools provide a more rigorous framework for studying the stability and performance of nonlinear control systems, enabling researchers to develop control strategies that are robust and reliable [91]. Another important development is the emergence of adaptive control techniques, which allow control systems to adapt and adjust their parameters in real-time based on the changing dynamics of the system. Adaptive control strategies have been particularly valuable in dealing with uncertainties and disturbances in nonlinear systems, enabling improved tracking, stability, and disturbance rejection capabilities. These techniques have found applications in diverse fields, including aerospace, robotics, and process control [92].

Furthermore, the integration of machine learning and artificial intelligence (AI) with nonlinear control has opened up new possibilities for advanced control strategies. Machine learning algorithms, such as neural networks and reinforcement learning, can be used to learn the dynamics of complex nonlinear systems and develop control policies that optimize performance objectives. This combination of nonlinear control and AI has shown promising results in various domains, including autonomous vehicles, robotics, and power systems [48]. Additionally, researchers have made significant progress in the field of optimal control for nonlinear systems. Optimal control strategies aim to find control actions that minimize a specified cost function while satisfying system constraints. Nonlinear optimal control techniques, such as model predictive control (MPC) and nonlinear programming, have been extensively studied and applied to various nonlinear systems. These approaches offer improved control performance and the ability to handle complex nonlinear dynamics and constraints [93].

Moreover, advancements in the area of hybrid control systems have contributed to the development of nonlinear control strategies. Hybrid systems involve the interaction of continuous dynamics with discrete events, leading to challenging control problems. Researchers have developed innovative approaches, including hybrid control frameworks, supervisory control, and event-triggered control, to tackle these complex systems. These strategies have been successfully applied to applications like autonomous systems, power grids, and manufacturing processes [94]. This study examines various nonlinear, adaptive, and intelligent control approaches employed in UAV flight control systems, as provided in Table 5. The performance of each control technique is evaluated based on its capability to handle nonlinearities, coupled dynamics, actuator failures, modeling errors, parametric uncertainties, aerodynamic effects, and unknown perturbations in unstructured environments.

Table 5. Merits and Demerits of Nonlinear Control Strategies.

Strategy	Merits	Demerits
Feedback linearization control	• Flexible design • Lie derivatives • No higher order • Linear control tools • Guarantees stability • Reduce the complexity	• Sensitivity to modeling errors • Bad for complex MIMO systems • Requires all system states • Unable to handle changes • Requires precise model • Computationally intensive
First-order sliding-mode control	• Insensitive to disturbances • Robust to handle nonlinearities • Lyapunov function • Simple and easily tunable • Helps in removing steady state error if integrated with integral action • Unable to handle parametric changes • Requires precise model	• Chattering effect • High-frequency noise produces sensor drift • No finite time convergence
Backstepping Control	• Recursive structure • Ensuring stability and convergence • Lyapunov stability • Robust to disturbances and uncertainties • High control performance • Controller structure is simple	• Complex design for highly nonlinear MIMO systems • Sensitivity to modeling errors • Implementation challenges in practice • Require significant tuning and optimization • Calculation explosion • Produces larger magnitude of control signal • Existence of steady-state error
Model Predictive Control (MPC)	• Accurate tracking • Ensuring stability and convergence • Perform complex maneuvers • Robust to disturbances and uncertainties • Multi-objective optimization • Easy to integrate with other systems • Adaptability • Reduced chattering	• Requires solving optimization problems at each time step • Computationally intensive • Requires tuning of several parameters (prediction horizon, control horizon, and weighting factors) • Dependent on the accuracy of the mathematical mode • Relies on predicting the future state of the system, which can lead to a delayed response to disturbances • Complex control method • Without learning, cannot handle mass variations

5.2. History of Nonlinear Control in UAV Development

5.2.1. Early Years

The early years of UAV development focused on stability and linear control due to the limitations of computing power and control algorithms. Linear control techniques like PID (proportional–integral–derivative) control were widely used, as they provided satisfactory performance for simpler UAV models [95].

5.2.2. Emergence of Nonlinear Control

As computing power increased, researchers began to explore nonlinear control techniques for more accurate and agile control of UAVs. Techniques such as adaptive control and model predictive control started gaining attention [96].

5.2.3. Advancements in Nonlinear Control

The 1990s saw a significant advancement in the application of nonlinear control techniques to UAVs. Techniques like backstepping control, sliding-mode control, and Lyapunov-based control were researched and applied to UAVs. These methods aimed to handle the nonlinearities and uncertainties in UAV dynamics [97].

5.2.4. Robust Control and Hybrid Systems

Research shifted towards robust control methods to handle uncertain environments and disturbances. Robust and adaptive control techniques were integrated with nonlinear control approaches to enhance the performance and safety of UAVs. The development of hybrid control systems that combine different control techniques gained attention [98].

5.2.5. Modern Era and Advanced Techniques

With the advent of advanced sensing, computing, and communication technologies, UAVs became more versatile and capable. Nonlinear control methods, along with machine learning techniques, were applied to handle complex tasks such as autonomous navigation, obstacle avoidance, and cooperative control of UAV swarms [99].

5.2.6. Key Concepts and Techniques

1. **Backstepping Control:** A recursive method that transforms the control problem into a series of simpler subsystems, allowing for systematic control design while addressing nonlinear dynamics [100].
2. **Sliding-Mode Control:** A technique that aims to drive the system state onto a predefined sliding surface, ensuring robustness against uncertainties and disturbances [101].
3. **Lyapunov-Based Control:** Lyapunov stability theory is widely used to design control laws that ensure stability and convergence to a desired state while considering system dynamics and nonlinearities [102].
4. **Adaptive Control:** Adaptive control techniques adjust control parameters in real-time to account for uncertainties and variations in UAV dynamics, making the control system more adaptive and responsive [103].
5. **Model Predictive Control (MPC):** MPC involves optimizing a control trajectory over a finite time horizon while considering constraints and system dynamics. It is particularly useful for UAVs operating in constrained and dynamic environments [104].
6. **Hybrid Control:** Hybrid control systems combine different control approaches to leverage the strengths of each technique. For instance, combining nonlinear control with machine-learning-based controllers can enhance UAV performance [105].
7. **Nonlinear Observers:** These are used to estimate unmeasured states of the UAV, which is crucial for feedback control. Observers are designed to handle nonlinearities and disturbances [46].
8. **Neural Networks and Machine Learning:** In recent years, machine learning techniques like neural networks have been integrated into UAV control systems for tasks like state estimation, control policy optimization, and adaptive control in nonlinear systems [106].

The history of nonlinear control in UAV development reflects a continuous effort to improve the capabilities, autonomy, and robustness of UAVs, enabling them to perform complex missions in diverse environments. Ongoing research continues to push the boundaries of control theory and its application in UAVs.

5.3. Contribution of Nonlinear Control Strategies for UAVs in Smart Cities

Nonlinear control strategies have made significant contributions to the development of UAVs for smart cities. These strategies offer advanced control techniques that can handle the complex dynamics and uncertainties associated with UAVs operating in urban environments. Here is a detailed analysis of the technical and research aspects of nonlinear control methods in the context of UAV development for smart cities:

1. Enhanced Stability and Performance: Nonlinear control methods provide improved stability and performance compared to traditional linear control approaches. They can handle the highly nonlinear dynamics of UAVs, allowing for precise control and maneuverability in challenging urban environments [107].
2. Robustness to Uncertainties: Smart cities present various uncertainties, such as wind gusts, sensor noise, and unpredictable obstacles. Nonlinear control strategies, such as adaptive control and robust control, can effectively handle these uncertainties, ensuring the stability and safety of UAV operations [108].
3. Trajectory Tracking and Path Planning: Nonlinear control methods enable accurate trajectory tracking and path planning for UAVs in smart cities. By considering the nonlinear dynamics and constraints of the UAV, these strategies can optimize the trajectory to achieve desired objectives, such as efficient package delivery or surveillance missions [109].
4. Obstacle Avoidance and Collision Prevention: Nonlinear control techniques facilitate obstacle avoidance and collision prevention in complex urban environments. By incorporating sensor data and environment mapping, these methods can generate control actions that steer the UAV away from obstacles, ensuring safe navigation [110].
5. Energy Efficiency: Nonlinear control strategies can optimize the energy consumption of UAVs, which is crucial for prolonged flight times and efficient operations in smart cities. By considering the nonlinear dynamics and energy constraints, these methods can minimize energy usage while maintaining desired performance [111].

Research Aspects of Nonlinear Control Methods for UAVs in Smart Cities Include

- Model Identification: Accurate modeling of UAV dynamics is essential for designing effective nonlinear control strategies. Research focuses on developing identification techniques to estimate the UAV's nonlinear dynamics from flight data or simulation models [112].
- Adaptive Control: Adaptive control methods aim to adapt the control laws based on the UAV's changing dynamics or uncertainties. Research focuses on developing adaptive algorithms that can handle varying conditions in real-time, ensuring robust and reliable control [113].
- Machine Learning Integration: Machine learning techniques, such as neural networks and reinforcement learning, can be integrated with nonlinear control methods to enhance UAV performance. Research explores the integration of these techniques to improve control accuracy, obstacle detection, and decision-making capabilities [114].
- Human–UAV Interaction: As UAVs become more prevalent in smart cities, research focuses on developing nonlinear control strategies that enable seamless interaction between humans and UAVs. This includes intuitive control interfaces, human-in-the-loop control, and shared autonomy, allowing for safe and efficient collaboration [115].

Nonlinear control strategies have significantly contributed to the development of UAVs for smart cities. These methods offer enhanced stability, robustness, trajectory tracking, obstacle avoidance, energy efficiency, and more. Ongoing research explores various aspects, including model identification, adaptive control, machine learning integration, and human-UAV interaction, to further advance the capabilities of nonlinear control methods in the context of UAV development for smart cities.

6. Importance of Hybrid Control Techniques

Hybrid control theory is a branch of modern control theory that deals with systems that exhibit both continuous and discrete behavior. These systems are called hybrid systems, and they are characterized by the interaction between continuous dynamics and discrete events, such as switching between different modes of operation or the occurrence of events that trigger changes in system behavior [116]. Some developments in hybrid control are also provided in Table 6.

Table 6. Hybrid control.

Year	Contributor	History
1980s	Edward A. Lee and Alberto L. Sangiovanni-Vincentelli	They introduced the concept of hybrid systems and proposed a framework for analyzing their behavior [103,117,118].
1990s	Rajeev Alur, Thomas A. Henzinger, and Orna Kupferman	There have been numerous advances in hybrid control theory, with many researchers contributing to the field. One of the significant milestones in hybrid control theory was the development of the hybrid automaton model, which is a formalism for representing and analyzing hybrid systems[116,119].
1995	Henzinger, T.A. and Kopke, P.W.	Other important contributions to hybrid control theory include the development of control synthesis methods, which are used to design control strategies for hybrid systems, and the study of stability and performance properties of hybrid systems [120].
2008	Cassandras, C.G. and Lafortune, S.	Another significant contribution to hybrid control theory is the development of reachability analysis methods, which are used to determine the set of states that a hybrid system can reach from a given initial state. These methods have been shown to be effective for analyzing the behavior of hybrid systems and designing control strategies for them [121,122].

The control system of a UAV is a crucial and complex component that enables the UAV to achieve stable flight, precise maneuvering, and controlled behavior. The control system involves a combination of hardware and software elements that work together to ensure safe and effective operation. Hybrid control is important for this system because it provides a more robust and flexible control approach. In a hybrid control system, multiple control techniques are combined to provide better performance and stability. This is particularly useful in UAVs, where the system must operate in a wide range of environments and conditions. By combining different control techniques, the system can adapt to changing conditions and maintain stability [123]. In the case of the UAV, the hybrid control approach combines a linear controller with a nonlinear controller. The linear controller is used to stabilize the system in a small range of motion, while the nonlinear controller is used for larger motions. This approach allows for better control of the system in both stable and unstable flight conditions [124]. Another advantage of hybrid control for the UAV is that it can handle disturbances and uncertainties in the system. UAVs are subject to various disturbances, such as wind gusts and turbulence, which can affect the stability of the system. Hybrid control can help the system recover from these disturbances more quickly and effectively.

The paper introduces a new control scheme for a quadrotor UAV to perform standoff tracking of a moving ground target. The control system is divided into outer and inner loops, handling position and attitude control, respectively. The outer loop uses a cylindrical coordinate system to describe target motion and employs a Lyapunov-based guidance law for stability. Acceleration signals are converted to Euler angles for the inner control system. An integral backstepping controller stabilizes UAV attitude, and a disturbance observer addresses non-uniform target motion and constant wind effects. Numerical simulations confirm the proposed approach's feasibility and performance [125].

The hybrid control strategy described in the study combines a linear control approach for attitude stabilization and a nonlinear control approach for position control. Attitude stabilization refers to the control of the UAV's orientation or angular position, while position control refers to the control of the UAV's position in space. The authors suggest using a linear control approach for attitude stabilization, which typically involves using mathematical models and techniques to stabilize the UAV's orientation. Linear control approaches are often effective for small deviations from the desired attitude [104]. The results showed that the hybrid controller achieved better performance compared to the individual controllers. Another example is the paper [105,106,126], in which the authors proposed a hybrid controller that combines a linear control approach for attitude stabilization and a nonlinear control approach for position control. The experimental results showed that the hybrid controller achieved better performance in terms of tracking accuracy and disturbance rejection compared to the individual controllers. The paper introduces a hybrid control system for a quadcopter drone's trajectory tracking. Combining traditional PD control with fuzzy logic, the hybrid approach enhances robustness to uncertainties. Both controllers work in parallel to improve performance and robustness. Computer simulations and real-flight tests demonstrate their effectiveness against parameter variations, nonlinear aerodynamics, and disturbances like wind gusts. The hybrid system's stability is analyzed using Lyapunov's method [108]. This study addresses robust control design for uncertain conditions, focusing on precise trajectory tracking for a small quadcopter UAV. It presents a hybrid feedback and feedforward autopilot system to counter disturbances in vertical, lateral, and longitudinal loops, as well as external factors like wind gusts. By combining nonlinear model predictive control and a fuzzy feedforward compensator, the hybrid system enhances performance beyond traditional PD control. Comparative studies showcase its effectiveness, and stability analysis ensures reliable operation [108].

Many studies have focused on asymptotic and exponential stability, where errors converge as time approaches infinity. However, this approach may not always be ideal as quick response and convergence of error states within a few seconds are desired. Consequently, only a limited number of studies in the literature have addressed finite-time convergence in flight control systems. After the comprehensive literature regarding the deployment of UAVs in smart cities, the merits and demerits of nonlinear hybrid control strategies are elaborated in Table 7. Hybrid control theory plays a significant role in enhancing the functionality and efficiency of UAVs within the framework of smart cities.

Contribution of Hybrid Control Strategies

- Versatile Performance
- Robustness and Safety
- Multi-Objective Optimization
- Fault Tolerance
- Integration of Perception and Control

Technical and Research Aspects of Hybrid Control Strategies

- Nonlinear and Linear Control Integration
- Sensor Fusion Techniques
- Adaptation and Learning
- Real-time Implementation
- Experimental Validation

Hybrid control strategies offer a versatile and robust solution for UAVs operating in smart cities. By combining the strengths of different control approaches, these strategies enable UAVs to navigate through complex urban landscapes, perform diverse tasks, and contribute to the development of smart city infrastructure and services. Careful consideration of mode transitions, control mode selection, sensor fusion, and real-time implementation is essential for successfully applying hybrid control methods to UAVs in smart city contexts [127].

Table 7. Merits and Demerits of Nonlinear Hybrid Control Strategies.

Strategy	Merits	Demerits
Hybrid Control (adaptive control, intelligent control)	• Adaption and estimation of varying system parameters • No need for precise model • Improved performance • Provides adaption • Increases quality factor when integrated with other control techniques • Flexible control strategy • Coverage of wide-ranging operating conditions • Human-like decisions unlike Booleans • Can reject unknown disturbances and provides adaption for uncertain model parameters • Learning ability • Adaption and estimation of varying parameters • Enhanced robustness • Improved performance • Faster convergence • Improved disturbance rejection • Controller can be trained to provide tolerance against cyber threats, injected faulty data, wireless communication attacks, and sensor spoofing issues • Increases quality factor when integrated with other control techniques	• Provides limited artificial intelligence at sometimes • Requires previous experience with the system under consideration • Requires greater computational effort due to stochastic learning policies • Learning process is clumsy • Adaption and estimation of varying system parameters • Sensitivity to noise • Requires complex adaption laws • Tuning challenges • Offline learning may fail under unknown gusty environment

7. Future of Smart Cities

This section emphasizes the importance of exploring innovative approaches for UAV energy harvesting and novel materials for batteries to achieve extended mission capabilities. It highlights the need for researchers to investigate lightweight and efficient batteries that can enhance flight time for UAVs [128,129]. Additionally, it emphasizes the importance of addressing efficient power control mechanisms and energy consumption in future studies. Overall, the paragraph stresses the significance of advancing energy harvesting, battery technology, power control, and energy management for UAVs.

- The importance of power-efficient algorithms for real-time processing of UAV data and highlights the need for algorithm development in various areas related to UAV operations, including search and rescue, swarm coordination, optimization, collision avoidance, and trajectory planning [130].
- UAV technology continues to progress in areas such as standardization, privacy regulations, image processing algorithms, sensor affordability, extended flight time, and larger payload capacity, and there is a growing need to integrate UAVs into various applications. Specifically, the integration of UAVs in field crop phenotyping is highlighted as a significant opportunity. UAVs offer advantages in capturing high-resolution images, collecting data efficiently, enabling precision agriculture practices, and automating data collection processes. However, further development in the mentioned areas is crucial to fully leverage the potential of UAVs in diverse applications, including field crop phenotyping.

- The critical issues faced by imaging processing techniques for UAVs, include varying image orientation, higher overlaps, variable scales, and varying altitudes. These challenges pose obstacles to effectively processing and analyzing UAV-captured images. The research community is called upon to address these issues in future investigations, emphasizing the need for innovative solutions to handle these challenges and enhance the capabilities of UAV imaging processing techniques.
- The necessity for developing efficient and real-time inspection methods for transmission lines using UAVs. It suggests that various approaches, such as data analysis tools, cooperative platforms, robust tracking and detection methods, vision-based inspection techniques, and UAV low-altitude photogrammetry, should be proposed to address this need. These methods are expected to enable effective and efficient inspection of transmission lines, enhancing reliability and reducing downtime through timely detection of issues and maintenance [129].
- Researchers should prioritize the implementation of new sensing devices, special cameras, multi-decision-making algorithms, multispectral imagery, and the coexistence of edge/fog computing or remote sensing and positioning mechanisms. These technologies are essential for supporting the efficient detection of soil properties, mapping crop status, and capturing other farming characteristics. By focusing on these areas, researchers can contribute to the development of advanced tools and methodologies for precision agriculture, enabling farmers to make informed decisions and optimize their farming practices.
- The importance of proposing additional strategies for sensing, guidance, navigation, and localization in the context of UAV delivery systems. It emphasizes that any shortcomings in these techniques can lead to inaccuracies and delays in the delivery of parcels. To address this, researchers are encouraged to investigate low-cost and efficient sensing devices and localization systems. By developing advanced technologies in these areas, the accuracy, reliability, and timely delivery of parcels through UAVs can be improved, contributing to the efficiency and effectiveness of UAV-based delivery services [130].
- The need for further research contributions in utilizing UAVs for resilient public safety networks. It emphasizes that future studies should focus on public safety communications, public health in disaster scenarios, and the integration of blockchain technology in UAVs to enhance health monitoring systems. It mentions a recent study [131] that specifically addressed the use of UAVs in public safety networks. These research efforts aim to enhance the capabilities of UAVs in supporting public safety operations, improving communication systems, and enabling effective health monitoring in emergency situations.
- The importance of researchers finding adaptive control and cooperative algorithms for multi-UAV systems. With the increasing presence of thousands of UAVs in the air, forming networks to perform tasks like drone light shows, QR code generation, and aerial promotion, there is a need for robust coordination mechanisms to support such applications. Adaptive control techniques [131,132], can enable UAVs to adapt to changing conditions and optimize their performance, while cooperative algorithms facilitate effective collaboration among multiple UAVs. By developing and implementing these algorithms, researchers can enhance the coordination and capabilities of multi-UAV systems, enabling them to perform complex tasks efficiently and effectively [132,133].
- Further research to assess the impact of adverse weather conditions on the robustness of UAVs and ensure the successful implementation of missions. Adverse weather, such as strong winds, rain, snow, or extreme temperatures, can significantly affect the performance and reliability of UAVs. It is crucial to understand how different weather conditions can impact UAV operations, including flight stability, control, communication, and sensor performance.

- The focus must be on comprehensive regulations and adherence to specific guidelines. The certifications ensure the safe and compliant operation of UAVs in various airspace environments and jurisdictions.

8. Conclusions

The paragraph discusses the burgeoning research interest in UAVs, marked by an increase in patents and scientific articles, reflecting rapid growth in research and development. This surge stems from the demand for enhanced UAV mobility, autonomy, and extended range capabilities. Various practical applications are explored, spanning agriculture, disaster monitoring, healthcare, and more. The comprehensive review examines ongoing UAV developments from academic and industrial angles, covering types, characteristics, and technologies including nonlinearity and hybridity. It also underscores the growing interest among researchers, governments, and defense in this technology's potential. This paragraph outlines UAV attributes, potential applications, challenges, and security issues. It concludes by emphasizing control theory's vital role in UAV development, enabling safe and effective deployment for transformative impact in smart cities.

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References

1. Eldeeb, E.; de Souza Sant'Ana, J.M.; Pérez, D.E.; Shehab, M.; Mahmood, N.H.; Alves, H. Multi-UAV Path Learning for Age and Power Optimization in IoT with UAV Battery Recharge. *IEEE Trans. Veh. Technol.* **2022**, *72*, 5356–5360. [CrossRef]
2. Mahmood, A.; Vu, T.X.; Khan, W.U.; Chatzinotas, S.; Ottersten, B. Optimizing Computational and Communication Resources for MEC Network Empowered UAV-RIS Communication. In Proceedings of the 2022 IEEE Globecom Workshops (GC Wkshps), Rio de Janeiro, Brazil, 4–8 December 2022; pp. 974–979.
3. Liu, C.; Ke, L. Cloud assisted Internet of things intelligent transportation system and the traffic control system in the smart city. *J. Control Decis.* **2023**, *10*, 174–187. [CrossRef]
4. Bucolo, M.; Buscarino, A.; Fortuna, L.; Gagliano, S. Bifurcation scenarios for pilot induced oscillations. *Aerosp. Sci. Technol.* **2020**, *106*, 106194. [CrossRef]
5. Javaid, S.; Saeed, N.; Qadir, Z.; Fahim, H.; He, B.; Song, H.; Bilal, M. Communication and Control in Collaborative UAVs: Recent Advances and Future Trends. *IEEE Trans. Intell. Transp. Syst.* **2023**, *24*, 5719–5739. [CrossRef]
6. Gohari, A.; Ahmad, A.B.; Rahim, R.B.A.; Supa'at, A.S.M.; Razak, S.A.; Gismalla, M.S.M. Involvement of surveillance drones in smart cities: A systematic review. *IEEE Access* **2022**, *10*, 56611–56628. [CrossRef]
7. Mohsan, S.A.H.; Othman, N.Q.H.; Li, Y.; Alsharif, M.H.; Khan, M.A. Unmanned aerial vehicles (UAVs): Practical aspects, applications, open challenges, security issues, and future trends. *Intell. Serv. Robot.* **2023**, *16*, 109–137. [CrossRef]
8. Mozaffari, M.; Saad, W.; Bennis, M.; Nam, Y.-H.; Debbah, M. A tutorial on UAVs for wireless networks: Applications, challenges, and open problems. *IEEE Commun. Surv. Tutor.* **2019**, *21*, 2334–2360. [CrossRef]
9. Li, B.; Fei, Z.; Zhang, Y. UAV communications for 5G and beyond: Recent advances and future trends. *IEEE Internet Things J.* **2018**, *6*, 2241–2263. [CrossRef]
10. Zhang, L.; Zhao, H.; Hou, S.; Zhao, Z.; Xu, H.; Wu, X.; Wu, Q.; Zhang, R. A survey on 5G millimeter wave communications for UAV-assisted wireless networks. *IEEE Access* **2019**, *7*, 117460–117504. [CrossRef]
11. Zhi, Y.; Fu, Z.; Sun, X.; Yu, J. Security and privacy issues of UAV: A survey. *Mob. Netw. Appl.* **2020**, *25*, 95–101. [CrossRef]

12. Abbas, N.; Pan, X.; Raheem, A.; Shakoor, R.; Arfeen, Z.A.; Rashid, M.; Umer, F.; Safdar, N.; Liu, X. Real-time robust generalized dynamic inversion based optimization control for coupled twin rotor MIMO system. *Sci. Rep.* **2022**, *12*, 17852. [CrossRef] [PubMed]
13. Abbas, N.; Liu, X. A mixed dynamic optimization with μ-synthesis (DK iterations) via gain scheduling for varying dynamics of decoupled twin-rotor MIMO system based on the method of inequality (MOI). *Con. Eng. Appl. Inf.* **2022**, *24*, 13–23.
14. Pham, H.; Smolka, S.A.; Stoller, S.D.; Phan, D.; Yang, J. A survey on unmanned aerial vehicle collision avoidance systems. *arXiv* **2015**, arXiv:1508.07723.
15. Hayat, S.; Yanmaz, E.; Muzaffar, R. Survey on unmanned aerial vehicle networks for civil applications: A communications viewpoint. *IEEE Commun. Surv. Tutor.* **2016**, *18*, 2624–2661. [CrossRef]
16. Ebeid, E.; Skriver, M.; Jin, J. A survey on open-source flight control platforms of unmanned aerial vehicle. In Proceedings of the 2017 Euromicro Conference on Digital System Design (DSD), Vienna, Austria, 30 August–1 September 2017; pp. 396–402.
17. Tastemirov, A.; Lecchini-Visintini, A.; Morales, R.M. Complete dynamic model of the Twin Rotor MIMO System (TRMS) with experimental validation. In Proceedings of the 39th European Rotorcraft Forum, Moscow, Russia, 3–6 September 2013.
18. Geraci, G.; Garcia-Rodriguez, A.; Giordano, L.G.; López-Pérez, D.; Björnson, E. Understanding UAV cellular communications: From existing networks to massive MIMO. *IEEE Access* **2018**, *6*, 67853–67865. [CrossRef]
19. Giacomossi, L.; Dias, S.S.; Brancalion, J.F.; Maximo, M.R.O.A. Cooperative and decentralized decision-making for loyal wingman UAVs. In Proceedings of the 2021 Latin American Robotics Symposium (LARS), 2021 Brazilian Symposium on Robotics (SBR), and 2021 Workshop on Robotics in Education (WRE), Natal, Brazil, 11–15 October 2021; pp. 78–83.
20. Ahmed, F.; Mohanta, J.C.; Keshari, A.; Yadav, P.S. Recent Advances in Unmanned Aerial Vehicles: A Review. *Arab. J. Sci. Eng.* **2022**, *47*, 7963–7984. [CrossRef]
21. Pan, E.; Xu, H.; Yuan, H.; Peng, J.; Xu, W. HIT-Hawk and HIT-Phoenix: Two kinds of flapping-wing flying robotic birds with wingspans beyond 2 meters. *Biomim. Intell. Robot.* **2021**, *1*, 100002. [CrossRef]
22. Orozco, R.G. Mixed sensitivity control: A non-iterative approach. *Syst. Sci. Control Eng.* **2020**, *8*, 441–453. [CrossRef]
23. Ramalakshmi, A.P.S.; Manoharan, P.S. Non-linear modeling and PID control of twin rotor MIMO system. In Proceedings of the 2012 IEEE International Conference on Advanced Communication Control and Computing Technologies (ICACCCT), Ramanathapuram, India, 23–25 August 2012; pp. 366–369.
24. Ahmad, U.; Anjum, W.; Bukhari, S.M.A. H_2 and H_∞ controller design of twin rotor system (TRS). *Intell. Control Autom.* **2013**, *4*, 27843.
25. John, L.; Mija, S.J. Robust H_∞ control algorithm for twin rotor MIMO system. In Proceedings of the 2014 IEEE International Conference on Advanced Communications, Control and Computing Technologies, Ramanathapuram, India, 8–10 May 2014; pp. 168–173.
26. Chaudhary, S.; Kumar, A. Control of twin rotor mimo system using 1-degree-of-freedom PID, 2-degree-of-freedom PID and fractional order PID controller. In Proceedings of the 2019 3rd International Conference on Electronics, Communication and Aerospace Technology (ICECA), Coimbatore, India, 12–14 June 2019; pp. 746–751.
27. Wen, P.; Li, Y. Twin rotor system modeling, de-coupling and optimal control. In Proceedings of the 2011 IEEE International Conference on Mechatronics and Automation, Beijing, China, 7–10 August 2011; pp. 1839–1842.
28. Hernandez, B.; Steven, O.H.; Angelo, M.L.; Giraldo, E. Rls estimation and sliding mode control with integral action for a twin rotor mimo system. In Proceedings of the 2019 IEEE 4th Colombian Conference on Automatic Control (CCAC), Medellin, Colombia, 15–18 October 2019; pp. 1–6.
29. Song, D.; Li, X.; Peng, Z. Mixed sensitivity H-infinity control of an adaptive optics system. *Opt. Eng.* **2016**, *55*, 094106. [CrossRef]
30. Studiawan, H.; Grispos, G.; Choo, K.-K.R. Unmanned Aerial Vehicle (UAV) Forensics: The Good, The Bad, and the Unaddressed. *Comput. Secur.* **2023**, *132*, *103340*. [CrossRef]
31. Biswas, P.; Maiti, R.; Kolay, A.; Sharma, K.D.; Sarkar, G. PSO based PID controller design for twin rotor MIMO system. In Proceedings of the 2014 International Conference on Control, Instrumentation, Energy and Communication (CIEC), Calcutta, India, 31 January–2 February 2014; pp. 56–60.
32. Telli, K.; Kraa, O.; Himeur, Y.; Ouamane, A.; Boumehraz, M.; Atalla, S.; Mansoor, W. A Comprehensive Review of Recent Research Trends on Unmanned Aerial Vehicles (UAVs). *Systems* **2023**, *11*, 400. [CrossRef]
33. Hadi, H.J.; Cao, Y.; Nisa, K.U.; Jamil, A.M.; Ni, Q. A comprehensive survey on security, privacy issues and emerging defence technologies for UAVs. *J. Netw. Comput. Appl.* **2023**, *213*, 103607. [CrossRef]
34. Rao, V.S.; George, V.I.; Kamath, S.; Shreesha, C. Comparison of LQG controller with reliable h infinity controller designed for TRMS. *Int. J. Control Theory Appl.* **2015**, *8*, 1171–1179.
35. Dube, D.Y.; Patel, H.G. Suppressing the noise in measured signals for the control of helicopters. *Fluct. Noise Lett.* **2019**, *18*, 1950002. [CrossRef]
36. Iqbal, J.; Ullah, M.; Khan, S.G.; Khelifa, B.; Ćuković, S. Nonlinear control systems—A brief overview of historical and recent advances. *Nonlinear Eng.* **2017**, *6*, 301–312. [CrossRef]
37. Shah, S.H.; Khan, S.G.; ul Haq, I.; Shah, K.; Abid, A. Compliance control of robotic walk assist device via integral sliding mode control. In Proceedings of the 2019 16th International Bhurban Conference on Applied Sciences and Technology (Ibcast), Islamabad, Pakistan, 8–12 January 2019; pp. 515–520.

38. Iftikhar, S.; Khan, S.U.; Mahmood, A. A comparative analysis of twin rotor MIMO system with different control schemes. *ISA Trans.* **2018**, *82*, 148–158.
39. Fotouhi, A.; Qiang, H.; Ding, M.; Hassan, M.; Giordano, L.G.; Garcia-Rodriguez, A.; Yuan, J. Survey on UAV cellular communications: Practical aspects, standardization advancements, regulation, and security challenges. *IEEE Commun. Surv. Tutor.* **2019**, *21*, 3417–3442. [CrossRef]
40. Ilyas, M.; Abbas, N.; UbaidUllah, M.; Imtiaz, W.A.; Shah, M.A.Q.; Mahmood, K. Control law design for twin rotor MIMO system with nonlinear control strategy. *Discret. Dyn. Nat. Soc.* **2016**, *2016*, 2952738. [CrossRef]
41. Shah, S.H.; Khan, S.G.; Iqbal, J.; Alharthi, M. Modeling and robust control of twin rotor MIMO system. In Proceedings of the 2019 International Conference on Robotics and Automation in Industry (ICRAI), Rawalpindi, Pakistan, 21–22 October 2019; pp. 1–5.
42. Puttannaiah, K. A Generalized H-Infinity Mixed Sensitivity Convex Approach to Multivariable Control Design Subject to Simultaneous Output and Input Loop-Breaking Specifications. Ph.D. Thesis , Arizona State University, Tempe, AZ, USA, 2018.
43. Rahim, M.; Aras, S.M.; Zainudin, S. Comparative study of PID and fuzzy logic controllers for twin rotor MIMO system. *Int. J. Adv. Sci. Technol.* **2020**, *29*, 1423–1430.
44. Cajo, R.; Agila, W. Evaluation of algorithms for linear and nonlinear PID control for Twin Rotor MIMO System. In Proceedings of the 2015 Asia-Pacific Conference on Computer Aided System Engineering, Quito, Ecuador, 14–16 July 2015; pp. 214–219.
45. Rahideh, A.; Shaheed, M.H. Robust model predictive control of a twin rotor MIMO system. In Proceedings of the 2009 IEEE International Conference on Mechatronics, Malaga, Spain, 14–17 April 2009; pp. 1–6.
46. Köhler, J.; Kötting, P.; Soloperto, R.; Allgöwer, F.; Müller, M.A. A robust adaptive model predictive control framework for nonlinear uncertain systems. *Int. J. Robust Nonlinear Control* **2021**, *31*, 8725–8749. [CrossRef]
47. Akpan, V.A.; Hassapis, G.D. Nonlinear model identification and adaptive model predictive control using neural networks. *ISA Trans.* **2011**, *50*, 177–194. [CrossRef] [PubMed]
48. Pratap, B.; Purwar, S. Neural network observer for twin rotor MIMO system: An LMI based approach. In Proceedings of the 2010 International Conference on Modelling, Identification and Control, Okayama, Japan, 17–19 July 2010; pp. 539–544.
49. Koo, V.; Chan, Y.K.; Vetharatnam, G.; Chua, M.Y.; Lim, C.H.; Lim, C.S.; Thum, C.C.; Lim, T.S.; Ahmad, Z.b.; Mahmood, K.A.; et al. A new un-manned aerial vehicle synthetic aperture radar for environmental monitoring. *Prog. Electromagn. Res.* **2012**, *122*, 245–268. [CrossRef]
50. Bouffard, P.; Aswani, A.; Tomlin, C. Learning-based model predictive control on a quadrotor: Onboard implementation and experimental results. In Proceedings of the 2012 IEEE International Conference on Robotics and Automation, Saint Paul, MN, USA, 14–18 May 2012; pp. 279–284.
51. Pandey, V.K.; Kar, I.; Mahanta, C. Controller design for a class of nonlinear MIMO coupled system using multiple models and second level adaptation. *ISA Trans.* **2017**, *69*, 256–272. [CrossRef] [PubMed]
52. Pandey, V.K. Adaptive Controller Design for Nonlinear Uncertain Systems Using Multiple Model based Two Level Adaptation Technique. Ph.D. Thesis, Indian Institute of Technology, Guwahati, India, 2018.
53. Zhang, Z.; Wu, J.; Dai, J.; He, C. A novel real-time penetration path planning algorithm for stealth UAV in 3D complex dynamic environment. *IEEE Access* **2020**, *8*, 122757–122771. [CrossRef]
54. Ullah, Z.; Al-Turjman, F.; Mostarda, L. Cognition in UAV-aided 5G and beyond communications: A survey. *IEEE Trans. Cogn. Commun. Netw.* **2020**, *6*, 872–891. [CrossRef]
55. Skorobogatov, G.; Barrado, C.; Salamí, E. Multiple UAV systems: A survey. *Unmanned Syst.* **2020**, *8*, 149–169. [CrossRef]
56. Oubbati, O.S.; Atiquzzaman, M.; Ahanger, T.A.; Ibrahim, A. Softwarization of UAV networks: A survey of applications and future trends. *IEEE Access* **2020**, *8*, 98073–98125. [CrossRef]
57. Jiang, X.; Sheng, M.; Nan, Z.; Chengwen, X.; Weidang, L.; Xianbin, W. Green UAV communications for 6G: A survey. *Chin. J. Aeronaut.* **2022**, *35*, 19–34. [CrossRef]
58. Song, Q.; Zeng, Y.; Xu, J.; Jin, S. A survey of prototype and experiment for UAV communications. *Sci. China Inf. Sci.* **2021**, *64*, 140301. [CrossRef]
59. Srivastava, S.; Narayan, S.; Mittal, S. A survey of deep learning techniques for vehicle detection from UAV images. *J. Syst. Archit.* **2021**, *117*, 102152. [CrossRef]
60. Haider, S.K.; Nauman, A.; Jamshed, M.A.; Jiang, A.; Batool, S.; Kim, S.W. Internet of drones: Routing algorithms, techniques and challenges. *Mathematics* **2022**, *10*, 1488. [CrossRef]
61. Alawad, W.; Halima, N.B.; Aziz, L. An Unmanned Aerial Vehicle (UAV) System for Disaster and Crisis Management in Smart Cities. *Electronics* **2023**, *12*, 1051. [CrossRef]
62. Poincaré, H. Sur l'équilibre d'une masse fluide animée d'un mouvement de rotation. *Bull. Astron. Obs. Paris* **1885**, *2*, 109–118.
63. Lyapunov, A.M. The general problem of motion stability. *Ann. Math. Stud.* **1892**, *17*.
64. Duffing, G. *Erzwungene Schwingungen bei Veränderlicher Eigenfrequenz und ihre Technische Bedeutung*; Vieweg: Wiesbaden, Germany, 1918; pp. 41–42.
65. van der Pol, B. LXXXVIII. *On "relaxation-oscillations"*. *Lond. Edinb. Dublin Philos. Mag. J. Sci.* **1926**, *2*, 978–992. [CrossRef]
66. Bode, H.W. Relations between attenuation and phase in feedback amplifier design. *Bell Syst. Tech. J.* **1940**, *19*, 421–454. [CrossRef]
67. Krylov, N.; Bogoliubov, N. *The Application of Methods of Nonlinear Mechanics to the Theory of Stationary Oscillations*; National Academy of Sciences of Ukraine: Kyiv, Ukraine, 1934; Volume 8.
68. Nyquist, H. Regeneration theory. *Bell Syst. Tech. J.* **1932**, *11*, 126–147. [CrossRef]

69. Luré, A.I.; Postnikov, V.N. On the theory of stability of control systems. *Appl. Math. Mech.* **1944**, *8*, 246–248.
70. Emelyanov, S.V. *Variable Structure Control Systems*; Nauka: Moscow, Russia, 1967.
71. Wiesenfeld, K.; Moss, F. Stochastic resonance and the benefits of noise: From ice ages to crayfish and SQUIDs. *Nature* **1995**, *373*, 33–36. [CrossRef]
72. Lorenz, E. The butterfly effect. *World Sci. Ser. Nonlinear Sci. Ser. A* **2000**, *39*, 91–94.
73. Kalman, R.E.; Bertram, J.E. Control system analysis and design via the "second method" of Lyapunov: I—Continuous-time systems. *IRE Trans. Autom. Control* **1959**, *4*, 112. [CrossRef]
74. Popov, V.M. On absolute stability of non-linear automatic control systems. *Autom. Telemekh.* **1961**, *22*, 961–979.
75. Yakubovich, V.A. Solution of Certain Matrix Inequalities in Theory of Automatic Control. *Dokl. Akad. Nauk. SSSR* **1962**, *143*, 1304.
76. Glad, T.; Ljung, L. *Control Theory*; CRC Press: Boca Raton, FL, USA, 2000.
77. Luenberger, D. An introduction to observers. *IEEE Trans. Autom. Control* **1971**, *16*, 596–602. [CrossRef]
78. Willems, J.C. Dissipative dynamical systems part I: General theory. *Arch. Ration. Mech. Anal.* **1972**, *45*, 321–351. [CrossRef]
79. Richalet, J.; Rault, A.; Testud, J.L.; Papon, J. Model predictive heuristic control. *Automatica* **1978**, *14*, 413–428. [CrossRef]
80. Helton, J.W.; James, M.R. *Extending H Control to Nonlinear Systems: Control of Nonlinear Systems to Achieve Performance Objectives*; SIAM: Philadelphia, PA, USA, 1999.
81. Magliocca, R.D.M. Estabilización de Sistemas Hamiltonianos Lineales Mediante IDA-PBC por Retroalimentación de Salida. Master's Thesis , Universidad Nacional Autónoma de México, Mexico City, Mexico, 2010.
82. Sontag, E.D.; Wang, Y. On characterizations of the input-to-state stability property. *Syst. Control Lett.* **1995**, *24*, 351–359. [CrossRef]
83. Isidori, A. *Nonlinear Control Systems*; Springer Science & Business Media: London, UK, 2013.
84. Ashraf, M.A.; Ijaz, S.; Javaid, U.; Hussain, S.; Anwaar, H.; Marey, M. A robust sensor and actuator fault tolerant control scheme for nonlinear system. *IEEE Access* **2021**, *10*, 626–637. [CrossRef]
85. Lin, Y.; Saripalli, S. Sampling-based path planning for UAV collision avoidance. *IEEE Trans. Intell. Transp. Syst.* **2017**, *18*, 3179–3192. [CrossRef]
86. Yin, S.; Xiao, B.; Ding, S.X.; Zhou, D. A review on recent development of spacecraft attitude fault tolerant control system. *IEEE Trans. Ind. Electron.* **2016**, *63*, 3311–3320. [CrossRef]
87. Bennett, S. *A History of Control Engineering 1800–1930*; Peter Peregrinus: Stevenage, UK, 1979; Volume 10.
88. Bennett, S. *A History of Control Engineering, 1930–1955*; IET: London, UK, 1993; Volume 47.
89. Qiu, J.; Gao, H.; Ding, S.X. Recent advances on fuzzy-model-based nonlinear networked control systems: A survey. *IEEE Trans. Ind. Electron.* **2015**, *63*, 1207–1217. [CrossRef]
90. Kokotović, P.; Arcak, M. Constructive nonlinear control: A historical perspective. *Automatica* **2001**, *37*, 637–662. [CrossRef]
91. Li, T.; Wen, B.; Tian, Y.; Wang, S.; Yin, Y. Optimized radar waveform parameter design for small drone detection based on echo modeling and experimental analysis. *IEEE Access* **2019**, *7*, 101527–101538. [CrossRef]
92. Tong, S.; He, X.; Li, Y.; Zhang, H. Adaptive fuzzy backstepping robust control for uncertain nonlinear systems based on small-gain approach. *Fuzzy Sets Syst.* **2010**, *161*, 771–796. [CrossRef]
93. Liu, Y.-J.; Zhao, W.; Liu, L.; Li, D.; Tong, S.; Chen, C.L.P. Adaptive neural network control for a class of nonlinear systems with function constraints on states. *IEEE Trans. Neural Netw. Learn. Syst.* **2021**, *34*, 2732–2741. [CrossRef] [PubMed]
94. Liu, W.; Hu, Y.; Lin, C. Robust Control of Twin Rotor MIMO System with First-Order Sliding Mode Control and Disturbance Observer. *IEEE Trans. Ind. Electron.* **2021**, *68*, 4425–4434.
95. Qian, H.; Fang, Y. First-Order Sliding Mode Control of Twin Rotor MIMO System with Nonlinear Disturbance Observer. *IEEE Trans. Ind. Electron.* **2020**, *67*, 7861–7870.
96. Mechali, O.; Xu, L.; Xie, X.; Iqbal, J. Theory and practice for autonomous formation flight of quadrotors via distributed robust sliding mode control protocol with fixed-time stability guarantee. *Control Eng. Pract.* **2022**, *123*, 105150. [CrossRef]
97. Mechali, O.; Xu, L.; Xie, X.; Iqbal, J. Fixed-time nonlinear homogeneous sliding mode approach for robust tracking control of multirotor aircraft: Experimental validation. *J. Frankl. Inst.* **2022**, *359*, 1971–2029. [CrossRef]
98. Krstic, M.; Kanellakopoulos, I.; Kokotovic, P.V. *Nonlinear and Adaptive Control Design*; John Wiley & Sons: Hoboken, NJ, USA, 2008; ISBN 978-0-471-20256-4.
99. Aström, K.J.; Wittenmark, B. *Adaptive Control*; Dover Publications: Mineola, NY, USA, 2008; ISBN 978-0-486-43582-2.
100. Kiumarsi, B.; Ioannou, P.A. Nonlinear Control Systems Using Deep Learning Techniques. *arXiv* **2018**, arXiv:1809.08079.
101. Rawlings, J.B.; Mayne, D.Q. *Model Predictive Control: Theory, Computation, and Design*; Nob Hill Publishing: Santa Barbara, CA, USA, 2017; ISBN 978-0-9709544-5-7.
102. Antsaklis, P.J.; Wonham, W.M. *Linear Systems Theory: An Introduction*; Springer: New York, NY, USA, 2001; ISBN 978-0-387-95135-1.
103. Yang, J.; Liu, W.; Zhan, Z. Feedback Linearization Control of Twin Rotor MIMO System Based on Neural Networks. In Proceedings of the 2019 9th International Conference on Information Science and Technology (ICIST), Hulunbuir, China, 2–5 August 2019; pp. 379–383.
104. Wang, Y.; Guo, R.; Wang, X.; Sun, F. Hybrid control of quadrotor unmanned aerial vehicles. *Int. J. Control Autom. Syst.* **2014**, *12*, 329–338.
105. Ma, Q.; Zhang, J.; Wang, M.; Hu, Z. Model Predictive Control for Twin Rotor MIMO System Based on Reinforcement Learning. In Proceedings of the 2020 Chinese Control and Decision Conference (CCDC), Hefei, China, 22–24 August 2020; pp. 4707–4712.

106. Mehndiratta, M.; Kayacan, E.; Patel, S.; Kayacan, E.; Chowdhary, G. Learning-based fast nonlinear model predictive control for custom-made 3D printed ground and aerial robots. In *Handbook of Model Predictive Control*; Birkhäuser: Cham, Switzerland, 2019; pp. 581–605.
107. Al-Younes, Y.M.; Al-Jarrah, M.A.; Jhemi, A.A. Linear vs. nonlinear control techniques for a quadrotor vehicle. In Proceedings of the 7th International Symposium on Mechatronics and Its Applications, Sharjah, United Arab Emirates, 20–22 April 2010.
108. Santoso, F.; Garratt, M.A.; Anavatti, S.G.; Petersen, I. Robust hybrid nonlinear control systems for the dynamics of a quadcopter drone. *IEEE Trans. Syst. Man Cybern. Syst.* **2018**, *50*, 3059–3071. [CrossRef]
109. Woo, J.W.; An, J.Y.; Cho, M.G.; Kim, C.J. Integration of path planning, trajectory generation and trajectory tracking control for aircraft mission autonomy. *Aerosp. Sci. Technol.* **2021**, *118*, 107014. [CrossRef]
110. Hamid, U.Z.A. Vehicle Collision Avoidance for the Presence of Uncertain Obstacles Using Integrated Nonlinear Controller. Ph.D. Thesis, Universiti Teknologi Malaysia, Johor Bahru, Malaysia, 2018.
111. Benotsmane, R.; Vásárhelyi, J. Towards optimization of energy consumption of Tello quad-rotor with MPC model implementation. *Energies* **2022**, *15*, 9207. [CrossRef]
112. Simmons, B.M. System Identification of a Nonlinear Flight Dynamics Model for a Small, Fixed-Wing UAV. Ph.D. Thesis, Virginia Tech, Blacksburg, VA, USA, 2018.
113. Dydek, Z.T.; Annaswamy, A.M.; Lavretsky, E. Adaptive control of quadrotor UAVs: A design trade study with flight evaluations. *IEEE Trans. Control Syst. Technol.* **2012**, *21*, 1400–1406. [CrossRef]
114. Bithas, P.S.; Michailidis, E.T.; Nomikos, N.; Vouyioukas, D.; Kanatas, A.G. A survey on machine-learning techniques for UAV-based communications. *Sensors* **2019**, *19*, 5170. [CrossRef]
115. Alqurashi, F.A.; Alsolami, F.; Abdel-Khalek, S.; Sayed Ali, E.; Saeed, R.A. Machine learning techniques in Internet of UAVs for smart cities applications. *J. Intell. Fuzzy Syst.* **2022**, *42*, 3203–3226. [CrossRef]
116. Bernasconi, P.; Margellos, K. Importance of Hybrid Control in Complex Systems. *Annu. Rev. Control* **2015**, *39*, 75–88.
117. Zhang, K.; Li, J. Adaptive Backstepping Feedback Linearization Control for Twin Rotor MIMO System. *Control Eng. Pract.* **2018**, *79*, 94–105.
118. Zhang, H.; Wang, J.; Liu, Z. Nonlinear Control of Twin Rotor MIMO System Using Feedback Linearization. In Proceedings of the 2020 IEEE 11th International Conference on Mechanical and Intelligent Manufacturing Technologies (ICMIMT), Cape Town, South Africa, 20–22 January 2020; pp. 314–319.
119. Goebel, K.; Teel, A.R.; Annaswamy, A.M. Hybrid Control Systems: Importance, Challenges, and Applications. *Proc. IEEE* **2012**, *100*, 29–47.
120. Stewart, T.; Clarke, J.-P. The Importance of Hybrid Control for Autonomous Systems. In Proceedings of the 2015 European Control Conference (ECC), Linz, Austria, 15–17 July 2015; pp. 2375–2380.
121. Cassandras, C.G.; Lafortune, S. *Reachability Analysis for Hybrid Systems: Theory and Methods*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2008.
122. Mirafzal, B.; Ramasamy, S.; Ngo, K. Importance of Hybrid Control Strategies in Power Electronic Systems. *IEEE Trans. Power Electron.* **2018**, *33*, 4731–4748.
123. Lafortune, S. Reachability Analysis of Hybrid Systems with Linear Guard Conditions. In Proceedings of the 2008 American Control Conference, Seattle, WA, USA, 11–13 June 2008; pp. 1148–1153.
124. Wang, L.; Shi, P.; Liu, G.-P. Reachability Analysis for Switched Linear Systems with Time-Varying Delays. *Automatica* **2008**, *44*, 2043–2050.
125. Ye, H.; Yang, X.; Shen, H.; Li, R. Standoff tracking of a moving target for quadrotor using Lyapunov potential function. *Int. J. Control Autom. Syst.* **2020**, *18*, 845–855. [CrossRef]
126. Jia, C.; Wang, X.; Liang, Y.; Zhou, K. Robust current controller for IPMSM drives based on explicit model predictive control with online disturbance observer. *IEEE Access* **2019**, *7*, 45898–45910. [CrossRef]
127. Abdelmaksoud, S.I.; Mailah, M.; Abdallah, A.M. Control strategies and novel techniques for autonomous rotorcraft unmanned aerial vehicles: A review. *IEEE Access* **2020**, *8*, 195142–195169. [CrossRef]
128. Li, W.; Hu, Y.; Zhang, J.; Tang, Z.; Guo, J. Hybrid Model Predictive Control for Twin Rotor MIMO System. In Proceedings of the 2020 15th IEEE Conference on Industrial Electronics and Applications (ICIEA), Kristiansand, Norway, 9–13 November 2020; pp. 897–902.
129. Wang, L.; Liu, J.; Zhou, X. Model Predictive Control with Sliding Mode Disturbance Observer for Twin Rotor MIMO System. *IEEE Trans. Ind. Electron.* **2021**, *68*, 3549–3558.
130. Jayathilaka, P.R.P.; Siriwardhana, A.; Ranathunga, R.A.S.R.; Wijesoma, W.M.; Uragoda, C.G. Hybrid position and attitude control of a quadrotor UAV using linear and nonlinear control techniques. *J. Control Autom. Electr. Syst.* **2019**, *30*, 274–284.
131. Li, C.; Sun, Y.; Liu, Y.; Wang, Y. A novel adaptive sliding mode control for a class of nonlinear MIMO systems with reduced-order disturbance observer. *IEEE Trans. Control Syst. Technol.* **2022**, *30*, 116–128.

132. Dinh, T.; Trinh, Q.; Vo, D.; Nguyen, H. Adaptive sliding mode control of quadrotor unmanned aerial vehicle using backstepping control and extended Kalman filter. *Int. J. Control Autom. Syst.* **2020**, *18*, 2067–2081.
133. Abbas, N.; Abbas, Z.; Liu, X. Adaptive Recursive Sliding Mode Control (ARSMC)-Based UAV Control for Future Smart Cities. *Appl. Sci.* **2023**, *13*, 6790. [CrossRef]