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Review

A Comprehensive Review of Recent Research Trends on Unmanned Aerial Vehicles (UAVs)

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Abstract: The growing interest in unmanned aerial vehicles (UAVs) from both the scientific and industrial sectors has attracted a wave of new researchers and substantial investments in this expansive field. However, due to the wide range of topics and subdomains within UAV research, newcomers may find themselves overwhelmed by the numerous options available. It is therefore crucial for those involved in UAV research to recognize its interdisciplinary nature and its connections with other disciplines. This paper presents a comprehensive overview of the UAV field, highlighting recent trends and advancements. Drawing on recent literature reviews and surveys, the review begins by classifying UAVs based on their flight characteristics. It then provides an overview of current research trends in UAVs, utilizing data from the Scopus database to quantify the number of scientific documents associated with each research direction and their interconnections. This paper also explores potential areas for further development in UAVs, including communication, artificial intelligence, remote sensing, miniaturization, swarming and cooperative control, and transformability. Additionally, it discusses the development of aircraft control, commonly used control techniques, and appropriate control algorithms in UAV research. Furthermore, this paper addresses the general hardware and software architecture of UAVs, their applications, and the key issues associated with them. It also provides an overview of current open source software and hardware projects in the UAV field. By presenting a comprehensive view of the UAV field, this paper aims to enhance our understanding of this rapidly evolving and highly interdisciplinary area of research.

Keywords: UAV; drone; research direction; open source projects; flight control; last three years; open projects; development; antennas; AI; ChatGPT

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1. Introduction

Artificial intelligence (AI) has become increasingly significant across various sectors due to its transformative capabilities, such as robotics, manufacturing and automation, healthcare [1], cybersecurity [2], education [3], energy and utilities [4,5], smart cities [6], natural language processing and human–computer interaction [7], agriculture [8], transportation and logistics [9]. Similarly, AI plays a critical role in unmanned aerial vehicles (UAVs), enhancing their capabilities in navigation [10], object detection [11], and mission planning [12].

The versatility and efficiency of UAVs have made them increasingly popular for a wide range of tasks. As the demand for UAVs continues to grow, it is crucial to stay updated with the latest developments and research in this field. UAVs have attracted significant attention in the scientific community, as demonstrated by numerous review papers [13–19] that explore the various aspects of UAV development and research across different applications. Several key areas have garnered particular interest in UAVs [18,20,21], including the use of open source hardware and software in recent UAVs [22–24], frame designing and optimization [25,26], control systems [27,28], both conventional [29] and modern [30,31] communication modalities (such as 5G networks), integration of AI [32], recognition and detection algorithms, and path planning strategies [33]. These areas play a pivotal role in advancing UAV technology and are critical subjects of investigation for researchers and practitioners alike.

Due to the wide range of subdomains and extensive scope of UAV research, coupled with significant investments in this multifaceted field, several important research questions have arisen. These include the interdisciplinary nature of UAV research, the challenges and opportunities presented by UAV technology, and the future directions of UAV research [34]. The field of UAVs has experienced rapid growth and has captured the attention of researchers worldwide. With its diverse subdomains and expansive nature, this field has become a vibrant and active area of study, attracting substantial investments. As researchers in this field, we are constantly seeking answers to pressing research questions. We recognize the need for a comprehensive guide to navigating the array of options available in UAV research [35].

The rapid growth and wide-ranging applications of unmanned aerial vehicles (UAVs) have given rise to several important research questions. One of these questions pertains to the interdisciplinary nature of UAV research. UAVs involve a convergence of various disciplines, including aerospace engineering, computer science, robotics, and remote sensing. Understanding the interplay between these disciplines and identifying effective collaboration strategies are crucial for advancing UAV technology [34]. Another important area of inquiry is the exploration of the challenges and opportunities presented by UAV technology. While UAVs offer numerous advantages such as improved efficiency, cost-effectiveness, and enhanced data collection capabilities, they also face challenges such as regulatory frameworks, privacy concerns, and safety issues. Investigating these challenges and finding solutions will contribute to the responsible and effective integration of UAVs into society [35]. As researchers in the field of UAVs, we recognize the importance of addressing these research questions. Our aim is to provide a comprehensive guide that navigates the vast landscape of UAV research. By synthesizing the latest findings and insights from various subdomains, we hope to provide a valuable resource for researchers and practitioners in this dynamic field. Through collaboration and knowledge sharing, we can collectively advance UAV technology and unlock its full potential in a wide range of applications.

In the realm of unmanned aerial vehicles (UAVs) or drones, several pressing research questions exist. Key among is exploring how we can enhance UAV autonomy by integrating machine learning and AI into their systems for improved functionality and decision making [34]. The improvement in navigation and control systems for precision maneuvers in unpredictable environments is a significant area of focus, as is developing advanced "sense and avoid" systems for reliable obstacle detection. The application of swarm intelligence in UAVs to facilitate collaborative tasks and the implementation of efficient algorithms is being studied [35]. Researchers are also looking into extending the UAV battery life and investigating efficient power management strategies and alternative energy sources. The ability to increase the UAV payload capacity without compromising efficiency or maneuverability and how drones can be adapted for specific payload types is under scrutiny. Equally important are the security concerns surrounding UAV systems against potential cyber-attacks or hijacking, and measures to protect individual privacy from the misuse of surveillance-capable UAVs. Questions abound about how UAVs can be safely incorporated into crowded airspace, particularly in urban environments or near airports, and what changes to air traffic control systems are required to accommodate them. The regulatory implications of widespread UAV use are also on the table, focusing on how laws and regulations should adapt to handle UAV use. Finally, the aspect of human–UAV interaction in terms of the safe and effective design for human interaction and improving the user experience is being delved into. Each of these research questions presents an exciting challenge in shaping the future of UAV technology.

In response to these needs, this paper serves as a comprehensive guide for new researchers venturing into the multifaceted and expansive subdomains of UAV research. Recognizing the vast scope of this field, the guide aims to establish a strong foundation for novice researchers by providing a thorough review and survey of each subfield. It encompasses popular UAV classifications [36], which categorize UAVs based on their size, range, and endurance. In addition to covering UAV classifications, this paper provides an overview of crucial aspects such as hardware architecture, recent research trends, open source initiatives, and software tools employed in UAV development and research. The research direction for UAVs has witnessed remarkable growth in recent years, and this paper meticulously analyzes these trends and investigates the interconnections among various research directions. Critical areas addressed in the paper include communication and antennas, the Internet of Things (IoTs), aircraft detection, control and autonomous flight, perception and sensing, energy-efficient flight, human–UAV interaction, swarm behavior, and more [18,20,21]. Notably, the paper highlights the significant impact of utilizing UAVs in animal studies, enabling non-invasive monitoring, precise data collection, and reduced disturbance to wildlife habitats [19,37]. By providing a comprehensive overview and synthesizing reliable references, this paper equips researchers with the necessary knowledge and resources to make significant contributions to the field of UAV research. It aims to foster exploration, innovation, and collaboration, ultimately driving the advancement and potential of UAV technology.

This paper explores potential open-development axes for UAVs, including AI integration [32], environmental monitoring [37–42], conservation [41,43], miniaturization [44], swarming and cooperative control [13,14,17,21], and transformability systems [45–48]. Aircraft control development is a crucial aspect of UAV research, necessitating the consideration of appropriate control algorithms and commonly used techniques [27,28], providing valuable insights into UAV research controls. The main contributions of this study are as follows:

- A comprehensive collection of relevant references related to the drone field, serving as a reliable and accessible source for researchers in this domain.
- Insights and predictions established through a rigorous scientific approach regarding the most active and rapidly expanding research directions in the UAV field over the past three years. The analysis is based on growth rate per year and acceleration, supported by robust evidence.
- Identification of potential UAV open development axes, offering valuable insights and ideas for future research directions. A systematic address of the consideration for the appropriate control algorithm of UAVs, providing an in-depth analysis of this critical aspect of UAV research.
- An overview of high-level UAV development software achieved through a systematic classification process, serving as an accessible guide to the available options in this area of UAV research.
- A rigorous extraction of the most prominent research directions in the UAV domain over the past three years, employing a scientifically sound methodology for a comprehensive understanding of the current state-of-the-art in UAV research.
- Presentation of a numerical analysis of the interrelationships among UAV research directions, offering clear insights into the current landscape of UAV research, facilitating the effective charting of future UAV research efforts.

2. Popular UAV Classification in Research

UAVs, also known as drones, can be classified based on several factors, such as their flying principle, mission, weight, propulsion, control, altitude range, configuration, purpose, launch method, payload, autonomy level, size, endurance, and range [36,49]. Common classifications of UAVs are as follows:

- Flying principle: This category includes fixed-wing, rotary-wing, hybrid, flapping-wing, and other types of UAVs that differ in their flying mechanism.
- Mission: UAVs can be classified based on their mission, such as reconnaissance, surveillance, attack, transport, search and rescue, and more.
- Weight: UAVs can be classified based on their weight, such as micro-UAVs, small UAVs, tactical UAVs, medium-altitude-long-endurance (MALE) UAVs, high-altitude-long-endurance (HALE) UAVs, and more.
- Propulsion: UAVs can be powered by electric, fuel, solar, or other sources.
- Control: UAVs can be remotely piloted, autonomous, semi-autonomous, or have other types of control.
- Altitude range: UAVs can be classified based on their altitude range, such as low-altitude UAVs, high-altitude UAVs, and stratospheric UAVs.
- Configuration: UAVs can have different configurations, such as mono-rotor, multi-rotor, tilt-rotor, tilt-wing, and others.
- Purpose: UAVs can have different purposes, such as military, civilian, commercial, industrial, scientific, and more.
- Launch method: UAVs can be launched from the ground, air, sea, or have other types of launch methods.
- Payload: UAVs can carry various payloads, such as sensors, cameras, communication systems, weapons, cargo, and others.
- Autonomy level: UAVs can have different levels of autonomy, such as fully autonomous, semi-autonomous, human-operated, and others.
- Size: UAVs can have different sizes, such as mini-UAVs, handheld UAVs, man-portable UAVs, vehicle-mounted UAVs, and more.
- Endurance: UAVs can have different endurance levels, such as short-endurance UAVs, long-endurance UAVs, ultra-long-endurance UAVs, and more.
- Range: UAVs can have different range levels, such as short-range UAVs, intermediate-range UAVs, long-range UAVs, and more.

These classifications enable us to categorize UAVs and understand their capabilities, limitations, and potential applications. The continuous development and evolution of UAV technology have led to the creation of new classifications and the blurring of traditional boundaries between them.

3. Navigating the Latest UAV Research Challenges

The primary objective of this review paper was to assess recent trends in UAV research over the past three years using the Scopus database as a reliable source. The database was queried using relevant keywords such as "drone", "UAV", "unmanned aerial vehicle", and "unmanned aerial systems". The obtained results were meticulously analyzed to identify the prominent research directions within this field. The number of scientific publications associated with each research direction was employed as an indicator of its significance and influence. This comprehensive analysis provides a comprehensive overview of the current state of UAV research and highlights the most promising avenues for future investigations. By gaining valuable insights into the prevailing areas of focus within the UAV research community, we can better comprehend the potential of this technology and its profound impact across various domains.

A systematic search was performed on the Scopus database using predetermined keywords in the title, abstract, and keyword fields. The search yielded a total of 47,635 references published in the UAV field between 2020 and 2023. The search was conducted on 14 March 2023. The chart below illustrates the resulting research directions, derived using the formula: (TITLE-ABS-KEY (uav) OR TITLE-ABS-KEY (drone) OR TITLE-ABS- KEY (unmanned AND aerial AND vehicle) OR TITLE-ABS-KEY (unmanned AND aerial AND systems)) AND PUBYEAR > 2019 AND PUBYEAR < 2024. Figure 1 presents a chart of the UAV research directions that have received significant attention in the last three years.

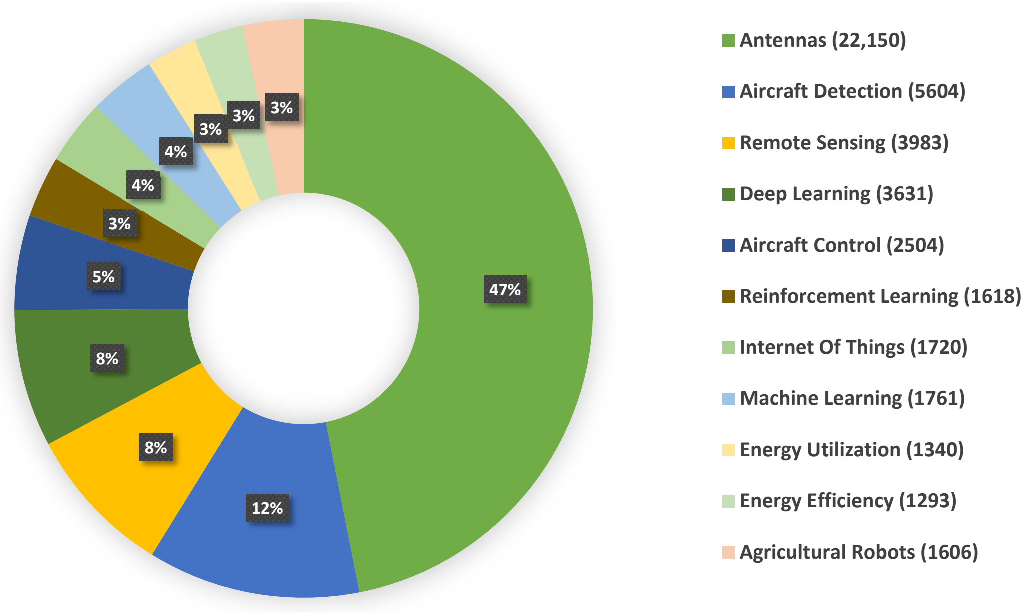


Figure 1. Distribution of the UAV research directions attracted significant attention in the last three years.

Over the past three years, there has been a surge in research efforts in the field of UAVs, with various areas of study being explored. Antennas, aircraft detection, remote sensing, deep learning (DL), reinforcement learning (RL), machine learning (ML), aircraft control, the IoTs, trajectories, energy utilization, and energy efficiency have emerged as the most prominent research directions [50]. The development of the aforementioned AI tools has revolutionized the UAV field, leading to improved performance in areas such as object detection, trajectory optimization, and mission planning. Moreover, research on human–UAV interaction, swarm behavior, environmental sensing, safety and reliability, integration with other platforms, application-specific development, and legal and ethical issues has also garnered significant attention in recent years [51].

The research direction of antennas in the UAV field has received the most attention, with 22,150 documents including journal papers, books, and conference papers, among others. This field has strong links to other research areas, such as aircraft detection, remote sensing, AI, IoT, and aircraft control. AI is the research area that interacts the most with antennas in UAVs, with 7010 documents, followed by Aircraft detection with 5604 documents, remote sensing with 3983 documents, aircraft control with 2504 documents, and IoT with 1720 documents, energy utilization and efficiency also areas that have attracted researchers, with 1340 and 1293 documents respectively, in the field of UAVs. Additionally, agricultural robots have garnered significant attention with 1606 documents. The interconnections between these research areas are depicted in Figure 2 and are further elaborated upon in Table 1. These results suggest that there is substantial overlap between research areas in UAV technology, which could lead to more integrated and efficient solutions in the future. The data were collected on 14 March 2023.

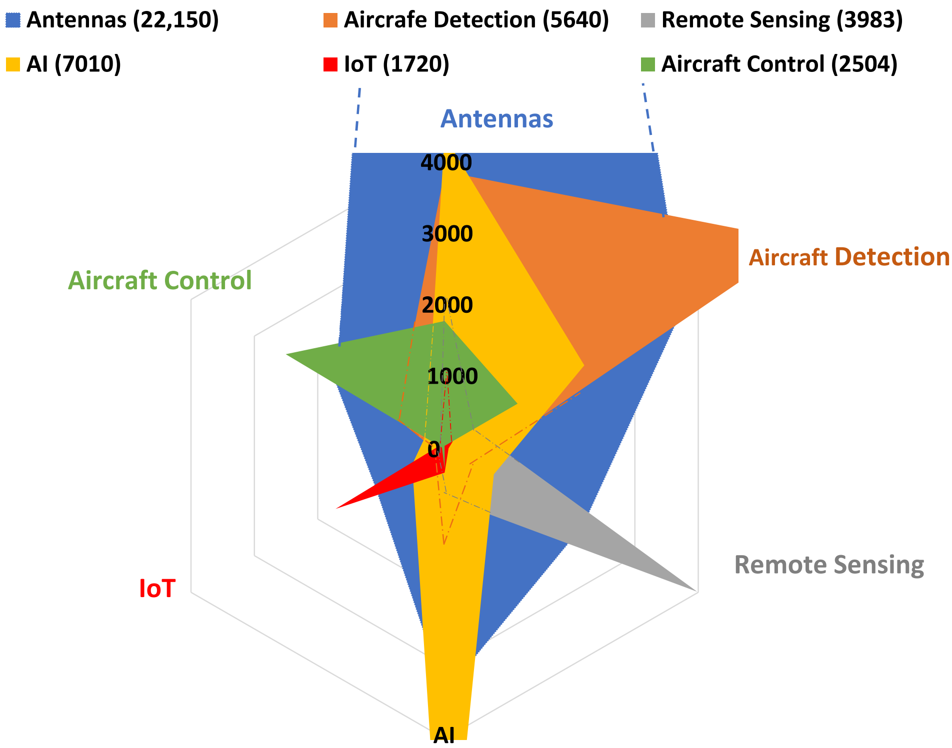


Figure 2. Overview of UAV research directions and the interactions among them in the last three years.

Table 1. Charting the course of UAV research: exploring emerging directions and the interactions among them.

Research Direction	Antennas	Aircraft Detection	Remote Sensing	AI	IoT	Aircraft Control
Antennas	22.150	3749	2176	3380	1092	1707
Aircraft Detection	3749	5604	0462	1343	0133	0758
Remote Sensing	2176	0462	3983	0707	0063	0
AI	4231	2203	0777	7010	0512	0294
IoT	1092	0133	0063	0365	1720	0043
Aircraft Control	1707	1152	0	0311	0043	2504

3.1. Communication and Antennas

The transmission and reception of signals are essential for the operation of UAVs, making antennas a critical component in their design. For UAV applications like communication [52–55], antennas need to be lightweight, compact, and durable enough to withstand harsh environmental conditions. Recent research into UAV antennas [52–59] has focused on developing advanced technologies to enhance UAV performance. Researchers are exploring ML and DL approaches for antenna design and optimization [57,60] as well as designing high-gain, wideband, and multibeam antennas and integrating them with other subsystems like power and control systems [55]. Table 2 portrays a comparison between the various communication technologies for FANETs.

Table 2. Comparison between the various communication technologies for FANETs [61,62].

Technology	Standard	Data Rate	Range
WiFi [63–67]	802.11 [13]	Up to 2 Mbps	Up to 100 m
LCY < 5 ms ǀ DM:Y ǀ	802.11 a [64]	Up to 54 Mbps	Up to 120 m
UL NT:WLAN	802.11 b [63]	Up to 11 Mbps	Up to 140 m
	802.11 n [65]	Up to 600 Mbps	Up to 250 m
	802.11 g [66]	Up to 54 Mbps	Up to 140 m
	802.11 ac [67]	Up to 866.7 Mbps	Up to 120 m
ZigBee [68,69]	802.15.4	Up to 25 kbps	Up to 100 m
LCY < 15 ms ǀ DM:Y ǀ UL			
Bluetooth V5 [70]	802.15.1	Up to 2 Mbps	Up to 200 m
LCY < 3 ms ǀ DM:Y ǀ UL			
LoRaWAN [71]	IEEE	Up to 50 kbps	Up to 15 km
DCD ǀ DM:Y ǀ UL	802.15.4 g		
NT:WPAN			
Sigfox [72]	-	Up to 100 bps	Up to 30 km
LCY about 2 s ǀ DM:Y ǀ UL			
NB-IoT [73]	-	Up to 250 kbps	Up to 35 km
LCY:1.6 to 10 s ǀ DM:Y ǀ L			
Cellular:			
3G [74–76]	HSPA+	Up to 21.1 Mbps	Wide area
LTE/LTEM		Up to 100 Mbps	
LCY:500 ms NT:LPWAN			
4G [72] LCY:4ms	HSPA+	Up to 100 Mbps	Wide area
5G [31,72,77,78]	mMTC	Up to 1 Gbps	Wide area
LCY:1 ms ǀ DM:Y ǀ L	URLLC	Up to 1 Gbps	Wide area
B5G [79]	eMBB/hybrid	Up to 100 Gbps	Wide area
LCY:1 ms ǀ DM:Y ǀ L	URLLC	Up to 100 Gbps	Wide area
6G [79,80]	MBRLLC	Up to 1 Tbps	Wide area
LCY< 1 ms ǀ DM:Y ǀ L	mURLLC	Up to 1 Tbps	Wide area
	HCS / MPS	Up to 1 Tbps	Wide area

DM: Device mobility; **LCY**: Latency; **Y**: YES; **DCD**: Device class dependent; **ST**: Spectrum type; **UL**: Unlicensed; **L**: licensed; **NT**: Network type.

Miniaturization of antennas and AI is also being studied to develop smaller and more agile UAVs with enhanced capabilities [57]. Furthermore, research on novel materials and manufacturing techniques such as 3D printing [59,81–83] has great potential to produce efficient and low-cost antennas for UAVs. Overall, the advancement of UAV technology and the development of more efficient and effective UAV systems for various applications depend on continued research into UAV antennas.

Flying ad hoc networks (FANETs) are wireless communication networks composed of drones. FANETs enable communication and collaboration among drones in a decentralized manner, without relying on a fixed infrastructure. FANETs are designed to operate in the sky, and they offer advantages such as improved coverage, increased mobility, and access to remote or inaccessible areas. FANETs utilize wireless communication technologies and specialized protocols to establish and maintain connections between drones, facilitating data and message exchange [72]. Through reviewing extensive literature, we extracted the information presented in Table 2. This provides a comprehensive comparison of different communication technologies utilized in FANETs.

3.2. IoTs

The integration of UAVs with IoTs has opened up new possibilities for data collection, analysis, and communication in various fields. By combining UAVs and IoT, a network of connected devices, sensors, and UAVs can collect, process, and share data in real time. Recent research [84–86] on IoT-enabled UAVs has focused on developing efficient and scalable communication protocols, network architectures [87], and data processing algorithms to enable the seamless integration and interoperability between UAVs and other IoT devices like sensors and data centers. IoT-enabled UAVs offer numerous benefits, such as improving the efficiency and effectiveness of various applications [88] and disaster management. For example, UAVs equipped with sensors can collect data on crop health, soil moisture, and temperature, which can be analyzed in real-time to inform irrigation and fertilization decisions. Similarly, UAVs can be used to monitor natural disasters and assess damage, enabling a more rapid and accurate response. Despite the immense potential of IoT-enabled UAVs, there are significant challenges that need to be addressed. Ensuring the security and privacy of IoT-enabled UAVs is crucial, and developing effective mechanisms for data processing and analysis is essential. However, the integration of UAVs with IoT is a promising area of research that has the potential to revolutionize various fields and enable new applications [89].

3.3. Aircraft Detection

Detecting and avoiding collisions with manned aircraft is a crucial task in the operation of UAVs, especially in shared airspace. The ability to detect aircraft is essential for ensuring the safe operation of both manned and unmanned aircraft. Recent research in the area of aircraft detection for UAVs has been focused on developing advanced systems that can detect and track aircraft in real-time using a range of sensors, including radar, LIDAR, and optical cameras. However, detecting small aircraft such as general aviation aircraft using traditional radar systems can be challenging. To address this issue, researchers are exploring the use of ML algorithms, such as DL, to improve the accuracy and reliability of aircraft detection systems. Integrating aircraft detection systems with UAVs' navigation and control systems is also a significant research direction. This integration can enable the automatic adjustment of UAVs' flight paths in response to the detected aircraft, ensuring the safe operation of both manned and unmanned aircraft. The research on aircraft detection for UAVs is crucial for enabling the widespread adoption of UAV technology in various domains, such as delivery, inspection, and surveillance, while ensuring safe operation in shared airspace.

3.4. Control and Autonomous Flight

Autonomous flight refers to the ability of UAVs to operate without human intervention, as achieved through the use of advanced control algorithms [17,28] and navigation systems that allow UAVs to fly, navigate, and perform tasks autonomously [17]. Autonomous flight is a complex and challenging area of research in the field of UAVs, requiring the integration of multiple technologies, such as sensors [90], computer vision [91], and AI [92]. The objective is to develop UAVs that can perform complex tasks in a safe and efficient manner, such as precision landing [91,93], without human intervention. One of the critical challenges in autonomous flight is developing UAVs that can navigate and avoid obstacles in real time while maintaining stability and control. This requires the development of advanced control algorithms [94] and sensors [90] that can accurately detect and respond to changes in the environment. Another significant challenge in autonomous flight is ensuring the safety and reliability of UAVs, particularly in scenarios with limited human intervention or hazardous areas [95]. To address these challenges, researchers are developing new approaches for monitoring, controlling, and diagnosing UAVs, including the integration of backup systems, failsafe mechanisms, and real-time monitoring systems. The goal of autonomous flight is to develop UAVs capable of performing a broad range of tasks safely, efficiently, and reliably without the need for human intervention. This has the potential to revolutionize various industries, including agriculture, logistics, military operations, search and rescue missions, and civil engineering applications.

3.5. Perception and Sensing

Perception and sensing are crucial capabilities of UAVs, allowing them to gather, process, and interpret information from their surroundings. These capabilities are essential for enabling UAVs to perform various tasks, such as navigation, mapping, inspection, and surveillance. However, these areas of research are complex and challenging, requiring the integration of multiple technologies, including sensors, computer vision, and AI. The ultimate aim is to develop UAVs that can perceive and understand their environment and make informed decisions based on that information. One of the key components of perception and sensing is the integration of various sensors, such as cameras, LiDAR, and radar [96,97]. These sensors provide UAVs with information about the environment, including the position and location of obstacles, terrain, and other objects. Another crucial aspect of perception and sensing is the development of computer vision algorithms that can process and interpret the information collected by the sensors. This includes identifying objects, recognizing patterns, and tracking movement. Additionally, researchers are exploring the integration of AI techniques, such as ML and DL [32], to enable UAVs to learn from their experiences and improve their perception and sensing capabilities over time. The ultimate goal of perception and sensing in UAVs is to develop systems that can accurately perceive and understand their environment and make informed decisions based on that information. This has the potential to revolutionize various industries, including agriculture [98], construction, civil applications [99], marine applications [39], mining [100], military operations, and search and rescue missions, such as wildfire remote sensing [101]. Furthermore, researchers are exploring the potential of cooperative perception using multiple UAVs to enhance their capabilities [102].

3.6. Energy-Efficient Flight

Energy-efficient flight is a critical area of research in the field of UAVs, aiming to develop drones that can fly for extended periods while consuming minimal energy. Achieving energy efficiency is essential to enhance the performance and capabilities of UAVs, including flight time, payload capacity, and range. Researchers are exploring several approaches [103], such as aerodynamic design optimization [103], lightweight materials, and the integration of alternative energy sources such as solar power [104]. Reducing the weight of UAVs is one of the key challenges in achieving energy-efficient flight. To address this, researchers are exploring the use of lightweight materials such as composites and new manufacturing techniques that can reduce the weight of UAVs. Moreover, the optimization of the propulsion system [105,106] is critical in achieving energy efficiency, including the use of more efficient engines and the development of new propulsion technologies [105]. Integrating electric and hybrid propulsion systems that offer improved energy efficiency compared to traditional internal combustion engines is also under research. Another area of research is the integration of alternative energy sources, such as solar power [107,108]. This involves developing new lightweight solar panels and energy storage systems capable of providing power for extended periods. Energy-efficient flight has the potential to significantly improve UAVs' capabilities and performance, enabling new applications and uses. However, massive data transfer during communication and surveillance can result in delays and considerable energy usage. Thus, deep reinforcement learning (DRL) and other AI approaches have been used in this context [109–111].

3.7. Human–UAV Interaction

Human–UAV interaction is an emerging field of research that investigates the interaction between humans and UAVs across various contexts, such as entertainment, education, and research. It has the potential to revolutionize several industries. Human–UAV interaction involves developing new technologies and interfaces that enable intuitive and innovative ways for humans to interact with UAVs [112]. These technologies include virtual and augmented reality, gestures [113], and other forms of human–machine interaction. One of the major challenges in human–UAV interaction is that of developing UAVs that can respond to human input in real-time while maintaining stability and control. This requires integrating advanced control algorithms and sensors and developing new user-friendly human–machine interfaces. Another challenge in human–UAV interaction is ensuring the safety and reliability of UAVs, particularly in scenarios where there is limited human intervention. Numerous approaches have been proposed for controlling UAVs using natural language, hand gestures, and physical movements. Intelligent human–UAV interaction systems have been developed, utilizing ML and DL techniques to recognize gestures and enable efficient control of the UAV [113–116]. Furthermore, some research papers have proposed novel architectures that allow users to control the UAV using natural body movements [117,118]. Alongside technical approaches, several studies have examined human factors and challenges related to the use of UAVs, such as user interfaces, training, and workload [119]. Another active area of research in human–UAV interaction is understanding human decision-making when controlling UAVs, particularly in search and rescue applications [120]. This highlights the importance of developing intuitive and efficient human–UAV interaction systems that can be used across various domains and applications. Survey papers have reviewed the current state-of-the-art in human–UAV interaction, such as a scoping review identifying areas like entertainment, transportation, and public safety, and another survey providing an overview of various control interfaces, gesture recognition techniques, and autonomous operation methods [121].

Furthermore, the literature has explored the human factors and challenges associated with using UAVs, including issues related to user interfaces, training, and workload [119]. Understanding human decision making when controlling UAVs is an active area of research, particularly in search and rescue applications [120]. This highlights the importance of developing intuitive and efficient human–UAV interaction systems that can be used in a wide range of domains and applications.

3.8. Swarm Behavior

Swarm behavior is a research area within the field of UAVs that aims to study the collective behavior of groups, or "swarms", of UAVs [122,123]. The potential impact of swarm behavior on various industries, such as military operations, search and rescue missions, and environmental monitoring, has driven the development of algorithms and control systems that enable UAVs to coordinate their actions and work together to achieve a common goal. One of the challenges in swarm behavior is to ensure effective collaboration between UAVs while adapting to changing conditions and environments. To address this challenge, researchers are developing new algorithms for cooperation and coordination, as well as new approaches for task allocation and resource management [28]. Additionally, the development of algorithms that enable UAVs to autonomously operate and make decisions based on their environment, including the integration of AI techniques such as ML and DL, is an important aspect of swarm behavior [33]. Communication and control architectures are essential for the successful operation of UAV swarms [124]. A review of UAV swarm communication and control architectures [28] highlights the need for scalable and flexible architectures to support different swarm configurations and tasks. Similarly, a review of UAV swarm communication architectures [124] discusses the challenges and future directions for communication in UAV swarms. Examples of communication and control architectures that can be used in UAV swarms include the high-level control of UAV swarms with RSSI-based position estimation [125] and a self-coordination algorithm (SCA) for multi-UAV systems using a fair scheduling queue [126].

Path planning is another critical aspect of swarm behavior. A recent review of AI applied to path planning in UAV swarms [33] discusses the latest developments in this field. The importance of motion planning in swarm behavior is highlighted in another paper that examines the motion planning of UAV swarms, recent challenges, and approaches [127]. Additionally, a study on collaborative UAV swarms towards coordination and control mechanisms [128] proposes a method for the collaborative motion planning of UAV swarms. Another important issue addressed in swarm behavior is localization in UAV swarms, which is tackled by the high-level control of UAV swarms with RSSI-based position estimation [125]. Finally, there are various applications of swarm behavior, including continuous patrolling in uncertain environments using the UAV swarm [129] and autonomous drone swarm navigation and multi-target tracking in 3D environments with dynamic obstacles [130]. In summary, research on swarm behavior for UAVs has been a rapidly growing area of study, with numerous advances made in recent years. The development of algorithms and control systems for cooperation, coordination, task allocation, and resource management has been a primary focus of research, as has the integration of AI techniques. Communication and control architectures, path planning, localization, and resiliency are also vital areas of research. The numerous applications of swarm behavior demonstrate the significant potential impact of this technology on various industries.

3.9. AI

The use of AI has had a significant impact on the field of UAVs in recent years. By enabling UAVs to perform tasks autonomously, AI has made them more efficient and effective in a variety of applications. Some of the most significant contributions and works related to using AI in UAVs include object detection [131–135] and tracking, path planning [33], autonomous navigation [92,136], swarm intelligence [33,122], image and video analysis [133,135], and cybersecurity [137].

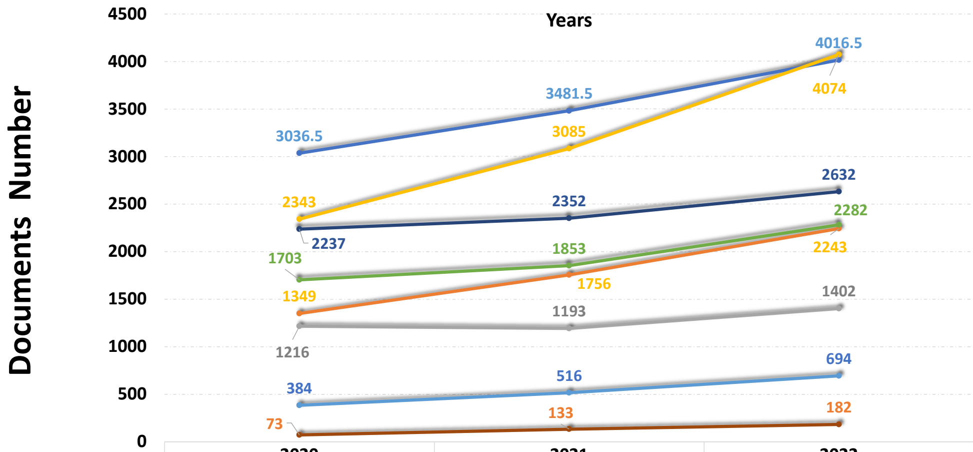
AI algorithms, such as convolutional neural networks (CNNs) and recurrent neural networks (RNNs), have been used to detect and track aircraft [133], objects [138–140], and real-time objects from UAVs [11,141], with applications in surveillance [111], search and rescue [141], and agriculture [8]. AI also enables UAVs to navigate autonomously in complex environments, avoid obstacles, and make real-time decisions based on sensor data [96], with applications in delivery, inspection, and surveillance [142]. Additionally, AI algorithms have been used to coordinate the behavior of multiple UAVs, forming a swarm that can perform tasks collaboratively [33,122], with applications in search and rescue, surveillance, and military operations.

Moreover, AI algorithms have been utilized to analyze images and videos captured by UAVs, extracting valuable information such as object recognition, semantic segmentation, and anomaly detection. These capabilities have a broad range of applications in fields such as agriculture, environmental monitoring, and disaster management. Additionally, AI has been used to detect and prevent cyberattacks on UAVs, ensuring their safety and security, with applications in military operations and commercial UAVs. Some notable works related to using AI in UAVs include recent examples that have received attention from the research community. These include DRL for UAV control, the vision-based autonomous landing of a fixed-wing UAV [91], swarm intelligence for collaborative UAV mission planning [33,122,143], the autonomous navigation of UAVs in indoor environments [92], and AI-based object detection and tracking for UAV surveillance [111,139,141]. These examples demonstrate the wide range of applications for AI in UAVs, including navigation, mission planning, object detection and tracking, and surveillance.

4. Active and Expanding UAV Research Directions

To conduct a comprehensive analysis, the Scopus database was used as the primary data source for extracting pertinent information regarding the research direction of UAVs over the past three years. The goal of this analysis was to (i) identify the main open challenges; and (ii) provide insights into the most active and rapidly expanding research directions in the UAV field over the last three years. To achieve this objective, a systematic search of the Scopus database was conducted using predefined keywords in the title, abstract, and keywords fields from January 2020 to December 2022. Research directions were delineated based on the identified publications, and the resultant growth trajectories were plotted, taking into account the linear relationship between the number of publications and time (y = ax + b), where y represents the number of publications, x represents the year, and b represents the number of publications in the previous year. Parameter a reflects the magnitude and rate of growth observed from year to year.

The results of this analysis are presented in Figure 3, depicting the growth trajectories of each research direction. Furthermore, Table 3 tabulates the average growth rate for each research direction to facilitate a better understanding of the growth dynamics in the UAV field.



	2020	2021	2022
Antenna x 0.5	3036.5	3481.5	4016.5
Aircraft Detection	1349	1756	2243
Remote Sensing	1216	1193	1402
AI	2343	3085	4074
IoT	384	516	694
Energy-Efficient	1703	1853	2282
Control	2237	2352	2632
Swarm Behavior	73	133	182

Figure 3. Overview of growth trajectories in UAV research directions in the last three years.

Table 3. Acceleration of growth in UAV research directions.

Research Direction	Rate of Growth/Year (Number of Documents/Year)	Acceleration of Growth
Antenna	980	1.20
Aircraft detection	447	1.19
Remote sensing	93	9.08
AI	865	1.33
IoT	155	1.34
Energy efficiency	289	2.86
Control	197	2.43
Swarm	54	0.81

The acceleration of growth shown in Table 3 demonstrates a high degree of efficacy in predicting the areas of interest that attract significant attention from researchers in the UAV domain. These predictions offer a nuanced perspective of the developments and trends within the field. For example, the antenna field has a considerable number of publications and an impressive growth rate of approximately 980 new documents per year. However, its growth ratio remains relatively constant at 1.20. In contrast, the field of remote sensing experiences a remarkable surge in interest each year, as reflected by an acceleration in the growth ratio of 9.08. Consequently, these findings provide valuable insights into the most promising research directions within the UAV domain.

5. Potentially Open Research Directions for UAVs

The open development axis for UAVs involves creating a collaborative ecosystem where developers, researchers, and users can work together to build open source platforms, tools, and standards for UAV design, development, and operation. This approach allows for greater innovation and flexibility in the UAV industry [20], including the integration of AI and ML algorithms to enhance autonomous flight and decision-making capabilities [144,145]. Further challenges and open research directions can be elaborated upon in the following points.

5.1. Integration of AI

AI algorithms are revolutionizing the way in which UAVs operate. By using these algorithms, UAVs can achieve improved autonomous flight and decision-making capabilities, which can result in more efficient and safer operations [144,145]. One-way AI and ML algorithms can be used in UAVs is through the development of advanced sensor systems. For example, computer vision and LIDAR can be integrated into UAVs to provide real-time data to the AI system [136]. This allows the UAV to make decisions based on its environment and dynamically react to changes. Computer vision can enable the UAV to recognize objects and people in its environment, which can be used to improve safety and prevent collisions. Meanwhile, LIDAR can provide detailed information about the UAV's surroundings, including the distance, size, and speed of the objects, which can be used to more effectively navigate complex environments.

Another way AI can be used in UAVs is through the optimization of flight paths. By using ML algorithms, UAVs can learn from past flights and optimize their routes to reduce energy consumption and increase efficiency. This can be achieved by analyzing data such as wind speed, temperature, and other environmental factors [143].

Generative AI and ChatGPT for UAVs

Natural language processing (NLP) models, like Chat Generative Pre-trained Transformer (ChatGPT) [146,147], are designed to understand natural language input from users and generate human-like responses. ChatGPT can be adapted to many robotics tasks, such as high-level agent planning [148] or code generation [149,150]. As such, it can serve as an intuitive language-based interface between non-technical users and UAVs.

"Efforts to incorporate language into robotics systems have largely focused on using language token embedding models,multi-modal model features, and LLM features for specific form factors or scenarios. Applications range from visual-language navigation [151], language-based human–robot interaction [152], and visual-language manipulation control" Ref. [153]. ChatGPT, for example, can be used via API libraries to enable many tasks [154], such as zero-shot task planning in drones, where it accesses functions that control a real drone and serves as an interface between the user and the drone [155]. This can allow non-technical users to easily and safely operate UAVs without needing specialized training.

A real drone was operated using ChatGPT through a separate API implementation, which offered a user-friendly natural language interface between the user and the robot, allowing the model to create intricate code structures for drone movement such as circular and lawnmower inspections [156]. Using the Microsoft AirSim [154,155] simulator, ChatGPT has also been applied to a simulated domain, where the possibility of a model being used by a non-technical user to operate a drone and carry out an industrial inspection scenario was investigated [156]. It can be seen from the snippet that ChatGPT can accurately control the drone by reading user input for geometrical clues and purpose.

5.2. Environmental Monitoring and Conservation

The utilization of UAVs for environmental monitoring and conservation presents a promising application of this advanced technology [38]. These unmanned aerial vehicles, equipped with high-resolution cameras and other cutting-edge sensors, offer immense potential for a wide range of purposes, including monitoring wildlife populations [40], tracking changes in ecosystems [157], and detecting environmental hazards [158]. By leveraging the capabilities of UAVs in these areas, we can greatly enhance our capacity to collect precise and reliable data, thereby gaining deeper insights into the overall health and well-being of our planet [159]. Such invaluable information empowers us to develop and implement effective conservation strategies, ensuring the preservation and safeguarding of our environment for future generations [160]. The use of drones in ecological and glaciological research in regions like Antarctica is on the rise, as demonstrated by studies [37,42,161]. Drones facilitate detailed geomorphological mapping, precise vegetation monitoring over expansive areas, and health indicator assessments. They enhance the identification and characterization of cryospheric features, including subsurface applications, and revolutionize faunal studies by enabling the non-invasive counting and morphometrics of diverse animal species [37]. UAV atmospheric surveys allow swift and versatile data collection, including aerosol sample collection. The design and development of platforms tailored to the harsh Antarctic environment have been crucial for the success of these applications. UAVs capable of collecting physical samples from remote or inaccessible areas are available, and further advances in autonomy and robustness will enhance their utility for Antarctic fieldwork [19]. UAV usage for environmental monitoring and conservation serves both planetary and human interests.

5.3. Urban Air Mobility (UAM)

UAM, an emerging field, holds immense promise for the future of transportation [162–164]. UAVs have the potential to revolutionize urban transportation by offering a rapid, efficient, and eco-friendly alternative to traditional ground-based systems [162]. However, realizing this potential necessitates significant technological advancements in navigation, autonomous flight, and safety systems. Moreover, the development of tailored air traffic management systems designed to address the unique challenges of urban environments is crucial for ensuring the safe and efficient operation of UAVs in densely populated areas [165]. With ongoing growth and investment in this domain, UAVs are poised to become a pivotal component of future urban transportation systems.

5.4. Miniaturization

In the UAV industry, miniaturization is a prominent trend that focuses on developing smaller and more compact drones capable of diverse applications [166]. These applications encompass search and rescue, delivery services, surveillance, and more. Nonetheless, accomplishing miniaturization necessitates substantial technological advancements, including the development of compact and efficient propulsion systems, as well as lighter and more durable materials. Consequently, miniaturization has emerged as a key area of research and development within the UAV industry, unlocking new possibilities for drone utilization across a wide range of fields.

5.5. Swarming and Cooperative Control

The open-development axis in the UAV industry focuses on establishing a collaborative ecosystem that brings together developers, researchers, and users to advance algorithms and techniques for the swarming and cooperative control of multiple UAVs, enabling them to perform complex tasks [28,122]. These tasks encompass a wide range of applications, including surveillance, search and rescue operations, and environmental monitoring. To achieve this, significant technological advancements are necessary, such as the development of robust communication protocols [28,124], distributed sensing and control systems [128], and adaptive decision making capabilities. For instance, the design of effective communication protocols facilitates seamless information exchange and coordination among multiple UAVs, enabling them to work together efficiently towards common objectives. Similarly, distributed sensing and control mechanisms empower each UAV to carry out specific tasks within a coordinated framework, greatly enhancing the efficiency and effectiveness of complex missions performed by UAV swarms. Additionally, the implementation of adaptive decision-making algorithms equips UAVs with the ability to make rapid and accurate decisions based on real-time data, further augmenting the capabilities of UAV swarms in various scenarios.

5.6. Beyond Visual Line-of-Sight (BVLOS) Operations

Beyond visual line-of-sight (BVLOS) operations refers to technologies that enable UAVs to operate beyond the visual line of sight of their pilot [167]. Achieving BVLOS capabilities requires the development of advanced sense-and-avoid systems capable of detecting obstacles and avoiding collisions [168]. Additionally, reliable communication and control protocols are necessary to ensure safe and efficient operations. To enable the widespread adoption of BVLOS operations, regulatory frameworks must be established to ensure compliance with safety standards and mitigate potential risks [169].

5.7. Long-Range and High-Altitude Flights

Another area of development in the UAV industry is the advancement of long-range and high-altitude flights. This entails equipping UAVs with the ability to fly for extended periods and at greater altitudes. To achieve this, there is a need for the development of more energy-efficient propulsion systems capable of sustaining long flights [170]. Additionally, the integration of renewable energy sources—such as solar panels—into UAV designs is being explored to extend their range and increase their endurance [171,172].

5.8. Flight Safety

As the use of UAVs continues to grow across different applications, ensuring flight safety has become a crucial concern. In response, developers are actively working on integrating new technologies that can enhance the safety of UAV operations. For instance, there has been an increasing focus on developing collision avoidance systems [173,174] that can prevent mid-air collisions with other UAVs, manned aircraft, or obstacles in the environment. Additionally, automatic landing systems [175] can help reduce the risk of accidents during landing, while onboard obstacle detection and avoidance systems [173] can enable UAVs to detect and avoid obstacles during flight, reducing the risk of collisions. Such technologies are critical for ensuring the safe and responsible use of UAVs, as these can mitigate potential risks and prevent accidents.

5.9. UAV Suspension Payload Capabilities

UAV suspension payload refers to the development and optimization of suspension systems for UAVs that are capable of carrying various types of payloads, including heavier items such as medical supplies, food, and other essential goods. The suspension system plays a critical role in ensuring stable flight during missions that involve payload dropping, as it helps to mitigate vibrations and provide shock absorption to protect the payload and sensitive equipment on board [176].

Recent advancements in drone suspension payload technology have focused on improving the performance and efficiency of suspension systems, as well as integrating them with other components of the drone. Some examples of these advancements include the use of advanced materials and manufacturing techniques, the development of active suspension systems that can adjust to changing flight conditions in real time, and the integration of suspension systems with propulsion, control, and payload systems to ensure seamless operation and maximum efficiency.

Moreover, recent advances in controlling quadrotors with suspended loads have focused on developing new algorithms and control strategies that can handle the additional complexity and challenges introduced by the suspended payload [177–179]. Some recent studies have proposed methods to improve the accuracy and stability of quadrotors with suspended loads, including predictive control strategies and the use of adaptive learning algorithms [177–179]. These innovations in UAV suspension payload technology will lead to more efficient and reliable delivery and transport capabilities, further expanding the applications of UAVs in various fields.

5.10. Transformability or Convertibility

Transformability or convertibility is an emerging technology in the field of unmanned aerial vehicles that enables them to change their shape or configuration in flight [45–47,180]. This advancement has the potential to enhance the versatility and efficiency of UAVs by allowing them to adapt to different operational environments and missions. There are several approaches to achieving transformability in UAVs, including:

One important area of transformability that we will explore is the utilization of morphing wings. This innovative approach involves designing wings capable of changing their shape during flight to enhance efficiency and maneuverability [181]. By incorporating morphing wings technology, drones can adapt their wing configurations to varying flight conditions, such as alterations in altitude, speed, and wind direction. Through these adaptable wings, drones can optimize their aerodynamic performance and overall efficiency, thereby improving their range, endurance, and stability [182]. There are several mechanisms employed to achieve morphing wings, including shape memory alloys, smart materials, and mechanical systems. These mechanisms enable drones to adjust the wing angle, alter the curvature of the airfoil, or even completely change the wing shape. One notable example of the morphing wings technology is the "RoboSwift", developed by the Delft University of Technology in the Netherlands. Resembling a swift bird in nature, this small drone has the ability to morph its wings during flight, allowing for enhanced efficiency and reduced noise. The RoboSwift has gained considerable recognition in the scientific community due to its innovative morphing wings technology and its potential applications in various fields, such as surveillance, environmental monitoring, and wildlife research. Its remarkable features have been highlighted in numerous research papers [183,184]. Another notable example is the "FlexFoil" developed by FlexSys Inc., Ann Arbor, MI, USA, an American engineering firm. The FlexFoil incorporates a unique "morphing trailing edge" technology, enabling the rear edge of the wing to bend and twist in response to changes in the airflow [185]. This design feature enhances the drone's aerodynamic performance and adaptability to different flight conditions, resulting in improved efficiency. By harnessing the power of morphing wings' technology, drones can revolutionize the field of aviation by achieving greater agility, range, and stability. The development of such transformative capabilities opens up new possibilities for various industries, from surveillance and monitoring to research and exploration.

The concept of foldable unmanned aerial vehicles (UAVs), equipped with collapsible arms or wings, presents an intriguing area for exploration [186]. This design feature leads to a decrease in the overall dimensions of the drones, thereby enhancing portability and facilitating more streamlined transportation and storage. Such foldable drones, including models like the Mavic Pro, DJI Mavic Air 2, Parrot Anafi, PowerVision PowerEgg X, and Robotics EVO, have gained substantial popularity due to their adaptability and convenience [187]. The ability of these drones to easily fold their arms or wings offers flexibility, allowing users to transport them in compact cases or bags. This feature not only improves portability, but also boosts the drones' durability and protection during transportation. Consequently, the potential damage is minimized, ensuring that the drones are well protected and ready for operation in a variety of environments and scenarios [188].

Moving on, reconfigurable airframes represents another avenue of transformation in UAVs. With reconfigurable airframes, drones have the ability to change their shape or configuration during flight to adapt to different missions or operational environments. This versatility can involve modifying their wing configuration, adding or removing payloads, or adjusting their center of gravity. By incorporating reconfigurable airframes, drones can cater to a wide range of mission requirements, making them more cost-effective and capable compared to traditional fixed-design drones. While reconfigurable airframes in UAVs are still an evolving technology, there are a few noteworthy examples of companies and organizations that are actively developing such drones [189]. For instance, roboticists from the University of Zurich and EPFL have developed quadrotors that feature foldable designs, allowing them to morph their shape in mid-air between "X" and "O" configurations [189,190]. These innovative designs demonstrate the potential of reconfigurable airframe drones, showcasing their adaptability and agility in various flight scenarios.

Additionally, the significant development in UAV technology is the incorporation ofvariable pitch propellers [191]. These propellers are equipped with blades that can adjust their angle or pitch during flight. Variable pitch propellers, also known as adjustable or controllable pitch propellers, provide a higher level of control over the drone's flight and performance, particularly under challenging or dynamic conditions. By altering the pitch of the propeller blades, the drone can finely tune its thrust and lift, enabling it to maintain stable flight even under varying wind conditions, altitudes, or flight modes. This capability greatly enhances the drone's maneuverability, efficiency, and overall performance across a wide range of applications, including aerial surveying, mapping, and inspection. Variable pitch propellers are commonly found in more advanced or specialized UAVs [192,193], such as industrial or military drones, where precise control and optimal performance are crucial. However, they are increasingly becoming accessible in consumer drones as well, allowing hobbyists and enthusiasts to leverage their benefits and enjoy greater control and versatility in their aerial endeavors.

Lastly, a significant advancement in UAV technology is the integration of transformable rotors [194,195]. UAVs equipped with transformable rotors have the ability to modify the configuration of their rotors during flight, enabling them to adapt to various flight conditions or mission requirements. This includes the capability to change the number or orientation of the rotors. The development of transformable UAVs holds tremendous potential in revolutionizing the field of unmanned aerial vehicles. It empowers UAVs to perform a broader range of missions with increased effectiveness and efficiency. One remarkable example is the VA-X4, which features four rotors that can tilt forward, transitioning from vertical takeoff and landing (VTOL) mode to forward flight mode. This design allows the UAV to achieve higher speeds of up to 200 mph, enabling it to more efficiently cover longer distances [194,195]. Another notable transformable rotor UAV is the Voliro Hexcopter developed by the ETH Zurich team [196,197]. This hexacopter utilizes multiple rotors capable of providing thrust in various directions, granting the drone the ability to translate freely and maneuver in complex environments. NASA's Greased Lightning GL-10 [198] is yet another remarkable transformable rotor UAV. It can seamlessly transition between a vertical takeoff and landing (VTOL) mode and a fixed-wing mode, optimizing efficiency during forward flight. This UAV is equipped with ten electric motors powering ten rotors, enabling it to achieve high speeds and exceptional maneuverability. These examples demonstrate the immense potential of transformable rotor UAVs in expanding the capabilities and versatility of unmanned aerial systems, paving the way for more efficient and adaptable aerial missions across various industries.

Overall, transformable UAVs have the potential to greatly improve the versatility and efficiency of UAVs, enabling them to adapt to different operational environments and missions. By transforming their shape or configuration in flight, these UAVs can optimize their performance for different flight conditions and mission requirements, making them a valuable tool for a wide range of applications.

6. Advancements in Aircraft Control: An Overview of the Development Axes

Flight dynamics control is a critical area of aerospace engineering that focuses on the stability and control of an aircraft during flight [28]. The main objective of flight dynamics control is to ensure that the aircraft remains stable, controllable, and safe across its entire flight envelope [199]. Various approaches and algorithms are employed in flight dynamics control to design control systems that stabilize and govern the behavior of aircraft throughout different flight tasks, including path following [200], morphing capabilities [45,47,48,180], navigation and surveillance [77], swarm flights [28], autonomous maneuvering [17], mapping [201], and sprayer operations [202]. These approaches and algorithms [27,28], along with their architectural considerations [28,203], utilize the mathematical models of aircraft dynamics and control theory to generate control inputs that modify the aircraft's behavior to achieve specific performance objectives [27]. The ultimate goal is to ensure safe, stable, and efficient flight operations.

There are several ways to classify UAV control methodologies [94,203,204], based on factors such as the type of UAV being controlled, the control objectives, and the mathematical techniques employed. Here are some common classifications in control theory: feedback control vs. feedforward control; linear control vs. nonlinear control [205]; continuous-time control vs. discrete-time control; deterministic control vs. stochastic control; model-based control vs. model-free control, robust control [206,207], and adaptive control [208,209]; centralized control vs. decentralized control; optimal control vs. suboptimal control; and time-invariant control vs. time-varying control. These classifications represent the different approaches and algorithms used in flight dynamics control. However, four main categories are widely recognized: classical control, modern control, intelligent control, and adaptive control, each offering distinct methodologies and techniques to address the complexities of flight dynamics control.

6.1. Classical Control

Classical control [210,211] refers to traditional control theory based on the mathematical models of linear systems. This approach is widely employed in controlling aircraft dynamics and involves the use of proportional, integral, and derivative (PID) control algorithms. The advantage of classical control lies in its simplicity and well-established theoretical foundations. However, it has limitations in handling nonlinear systems and managing disturbances that impact the aircraft's performance.

6.2. Modern Control

Modern control [211] encompasses the use of advanced control theory, including state-space and optimal control, to design control systems capable of handling nonlinearities and disturbances. This approach is extensively applied in flight dynamics control, as it provides more precise control and can manage complex systems. The advantage of modern control is its ability to handle nonlinear systems and uncertainties [212]. However, it requires more computational power and sophisticated algorithms, posing challenges for real-time implementation. The linear quadratic regulator (LQR) is a popular control algorithm widely used in flight dynamics control for the optimal control of linear systems.

6.3. Intelligent Control

Intelligent control [213–215] is a branch of control theory that employs AI techniques, such as neural networks, fuzzy logic, and genetic algorithms, to design control systems. This approach finds extensive use in flight dynamics control, as it can adapt to changing conditions and provide a high level of robustness. The advantage of intelligent control lies in its ability to handle complex and nonlinear systems, along with its adaptive nature. However, it requires significant computational resources and can be challenging to analyze and debug. Neural networks are widely employed in flight dynamics control, particularly for control and fault diagnosis. They have found applications in autopilots, flight control systems, and engine control systems.

6.4. Adaptive Control

Adaptive control is a class of control algorithms that can dynamically adjust control parameters in real-time based on the aircraft's behavior and environmental conditions [208].

This approach is widely employed in flight dynamics control as it effectively handles uncertainties and disturbances, making it suitable for variable operating conditions. The advantage of adaptive control lies in its ability to accommodate uncertain systems and adapt to changing conditions. However, it requires a substantial amount of data to learn the system's behavior, which can be challenging to obtain in certain cases. The model reference adaptive control (MRAC) is a widely used adaptive control algorithm in flight dynamics control, finding applications in various aircraft control systems, including autopilots, flight directors, and flight control systems [209].

In summary, flight dynamics control approaches and algorithms play a critical role in ensuring the safe and efficient operation of aircraft. The different classes of control techniques possess their respective strengths and weaknesses, and the choice of a particular approach depends on the specific requirements of the control problem. Researchers and practitioners continue to develop and enhance control systems for aircraft, and new approaches and algorithms are expected to emerge. In conclusion, flight dynamics control is an essential field of aerospace engineering that ensures the stability and controllability of an aircraft during its flight. Static stability control, dynamic stability control, and maneuverability control are the three primary classifications of flight dynamics control. Each class has its own advantages and disadvantages, and their selection depends on the specific design requirements of the aircraft.

6.5. Pushing the Boundaries of UAV Control: Exploring Advanced Techniques

In addition to the widely used PID control, the field of UAV control employs several advanced control techniques that aim to enhance performance and stability [216–218]. These techniques are particularly suited for complex and dynamic UAV systems. One prominent advanced control technique in UAV control is model predictive control (MPC). MPC utilizes mathematical models of the UAV's dynamics to predict its future behavior [219,220]. Based on these predictions, control inputs are computed to optimize a predefined performance metric, such as energy consumption, stability, or trajectory tracking accuracy. By considering the UAV's entire future trajectory, MPC offers improved performance compared to traditional control techniques. Another significantly advanced control technique is adaptive control. Adaptive control adjusts its parameters in real-time to adapt to changes in the UAV's environment and dynamics. This enables the control system to continuously enhance its performance over time, even in the presence of uncertainties and disturbances [209,221,222]. These advanced control techniques contribute to the development of more robust and efficient UAV control systems. Sliding mode control (SMC) is another advanced control technique that is widely used in UAV control. SMC is a nonlinear control technique that provides a robust performance in the presence of uncertainties and disturbances. SMC works by maintaining the UAV's states within a desired operating region, known as the sliding mode, which ensures stability and robustness [223,224]. Finally, there are several advanced control techniques that are based on ML as AI, such as RL and DRL [215,217], and neural network-based control [213,217]. These techniques enable UAVs to learn from their experiences and improve their control performance over time. In conclusion, there are several advanced control techniques that are being used in the field of UAV control. These techniques provide improved performance and stability compared to traditional control techniques, and they are well suited to the complex and dynamic requirements of UAV systems. Cooperative control is a technique that enables multiple UAVs to work together to achieve a common mission objective. Cooperative control is particularly useful for UAVs that need to perform complex tasks [225], such as surveillance or search and rescue, that require coordination and collaboration between multiple UAVs.

SMC is a widely utilized advanced control technique in UAV control. SMC is a nonlinear control method that ensures robust performance, even in the presence of uncertainties and disturbances. By maintaining the UAV's states within a desired operating region, known as the sliding mode, SMC guarantees stability and robustness [223,224]. The core concept of SMC lies in the creation of a sliding surface, which is a manifold in the state space.

The sliding surface is carefully designed to have attractive properties, such as finite-time convergence or robustness against parameter variations. The control law then acts upon the system to drive its state trajectory towards this sliding surface and maintain it there [226]. The distinguishing feature of SMC is its discontinuous nature (Chattering) [227]. The control law consists of multiple control actions, or switching functions, that are activated based on the relative position of the system state with respect to the sliding surface. When the system's state is not on the sliding surface, the control law switches between different modes or control actions to robustly drive the state towards the sliding surface. Once the state reaches the sliding surface, the control law switches to a different mode to maintain the system's trajectory on the surface [226–228]. The discontinuous nature of SMC offers robustness against uncertainties and disturbances since the control actions adapt rapidly based on the state's proximity to the sliding surface. Moreover, the sliding mode itself provides inherent robustness properties as the system's behavior on the sliding surface is less sensitive to parameter variations or external disturbances. Mathematically, SMC relies on the theory of differential inclusions and Lyapunov stability analysis to guarantee the system's convergence to the sliding surface and the subsequent maintenance of the system's behavior on the surface [228].

The general approach to designing SMC components is to start by defining a sliding surface that represents the desired behavior of the system. The sliding surface should have attractive properties, such as ensuring stability, convergence, or robustness. The choice of the sliding surface depends on the specific control objective and system dynamics. One commonly used sliding surface in quadrotor control is based on the error between the desired state and the actual state of the UAV. The sliding surface is designed to drive the error dynamics to zero. There are various possible sliding surfaces that can be used based on different UAV objectives and system dynamics. Several sliding surface design strategies have been proposed to minimize or eliminate the reaching mode [229]. These methods can be classified based on dimensions, linearity, time dependence, and the nature of their moving algorithm [223,229]. The aforementioned conventional sliding surface naturally yields a proportional–derivative (PD) sliding surface. To obtain PID structures, an integral action can also be included. Incorporating the integral term is commonly performed in conjunction with a boundary layer SMC approach. By including the integral term, the steady-state error resulting from the boundary layer can be eliminated [229]. The author in [229] has conducted extensive work in classifying the sliding surface into different categories, including linear constant sliding surface, linear discretely moving sliding surface, linear continuously moving sliding surface, constant nonlinear sliding surface, and nonlinear time-varying sliding surface. All these sliding surfaces are designed to improve controller performance by minimizing or eliminating the time required to reach the sliding phase. The second step in SMC design is to determine the equivalent control law and switching Law. After defining the sliding surface, the equivalent control law is derived to drive the system dynamics onto the sliding surface and maintain them there. The equivalent control law is typically obtained by analyzing the system's dynamic equation, which is designed to ensure that the system exhibits desirable behavior and achieves the control objectives. It involves determining a control signal that will force the system state to follow the sliding surface and stabilize the system. The control law should be designed to counteract the effects of uncertainties, disturbances, and nonlinearities in the system. The switching law is a crucial component that ensures the system's states remain on the sliding surface. It plays a key role in rejecting disturbances, uncertainties, and other external factors that may affect the system's performance. By employing a discontinuous control signal, specifically a set-valued control signal, this signal compels the system to "slide" along a section of its typical behavior [230]. There exist various types of reaching laws for SMC, including switching and non-switching reaching laws [230]. Additionally, a new non-switching reaching law has been introduced, demonstrating improved system robustness without amplifying the magnitude of critical signals in the system [230]. Non-switching reaching laws eliminate the need for switching across the sliding hyperplane in each subsequent step [231]. Additionally, a new non-switching reaching law has been introduced, demonstrating improved system robustness without amplifying the magnitude of critical signals in the system [230]. Non-switching reaching laws eliminate the need for switching across the sliding hyperplane in each subsequent step [231].

ML techniques, including RL, DRL [215,217], and neural network-based control [213,217] empower UAVs to learn from their experiences and continually enhance their control performance over time. UAVs have greatly benefited from the application of ML, which has enabled them to efficiently perform assigned tasks [92]. Researchers have explored the potential of UAVs in various areas such as inspection, delivery, and surveillance [92]. ML techniques have been employed to provide control strategies, including adaptive control in uncertain environments, real-time path planning, and object recognition [92]. An interesting approach to UAV control using ML is DRL. This method allows UAVs to autonomously discover optimal control laws by interacting with the system and handling complex nonlinear dynamics [232]. Remarkably, DRL has demonstrated success in the attitude control of fixed-wing UAVs using the original nonlinear dynamics with as little as three minutes of flight data [232]. The integration of ML has not only enhanced UAV capabilities but also reduced challenges, opening doors to various sectors [233]. This combination has yielded fast and reliable results [233]. In the realm of UAV flight controller designs, model-based control (MBC) techniques have traditionally dominated. However, they heavily rely on accurate mathematical models of the real plant and face complexity issues. Artificial neural networks (ANNs) offer a promising solution to address these challenges due to their unique features and advantages in system identification and controller design [234]. A comprehensive survey examines the combination of MBC and ANNs for UAV flight control, particularly in low-level control [234]. The objective is to establish a foundation and facilitate efficient controller designs with performance guarantees [234]. Fuzzy logic has been utilized to design autonomous flight control systems for UAVs [235]. For instance, a study focused on UAV flight dynamics and developed longitudinal and lateral controllers based on fuzzy logic [236]. Despite not employing optimization techniques or dynamic model knowledge, the fuzzy logic controller exhibited satisfactory performance [236]. Another example involves an ANFIS-based autonomous flight controller for UAVs, which utilizes three fuzzy logic modules to control the UAV's position in three-dimensional space, including altitude and longitude-latitude location [237]. In summary, the field of UAV control encompasses several advanced techniques that offer improved performance and stability compared to traditional control approaches. These techniques are well suited to meet the complex and dynamic requirements of UAV systems.

Cooperative control is a technique that facilitates the collaboration of multiple UAVs to accomplish a shared mission objective. Particularly for tasks like surveillance or search and rescue, where coordination and collaboration among multiple UAVs are essential, cooperative control proves to be highly beneficial [225]. The cooperative control of UAVs entails the effective coordination and collaboration among multiple drones to accomplish shared goals [238]. UAV swarms bring forth advantages in terms of improved efficiency, flexibility, accuracy, robustness, and reliability [238]. Nevertheless, the integration of external communications introduces the possibility of encountering additional faults, failures, uncertainties, and cyberattacks, which can potentially result in the propagation of errors [238]. For the purpose of ensuring operational safety, the field of cooperative control has seen the development of fault detection and diagnosis (FDD) and fault-tolerant control (FTC) methods [239]. These methods are designed to identify and tolerate faults that may occur in the individual components of UAVs [239]. The FDD unit is responsible for diagnosing faults, while the FTC unit offers appropriate compensation measures [239]. Cooperative UAVs find wide-ranging applications in diverse fields such as search and rescue operations, border patrol, mapping tasks, surveillance missions, and military operations [240]. These tasks are well suited to autonomous vehicles due to their repetitive or dangerous nature. The utilization of multiple UAVs substantially enhances the efficiency of execution [240]. In the realm of cooperative control, recent advancements encompass the introduction of a distributed consensus algorithm for multi-agent systems (MASs). This algorithm ensures the delivery of seamless input signals to control channels, effectively mitigating the undesired chattering effect associated with conventional control protocols [241]. Another innovative concept is cooperative fault detection and diagnosis (CFDD) and fault-tolerant cooperative control (FTCC), which mitigate the negative impact of the component and communication faults that may arise during formation or swarm flights [239]. Within the cooperative control architecture, drones collect sensory data, communicate, and share information [238]. Tasks are assigned based on mission requirements, and optimal paths are generated [238]. Control algorithms ensure precise trajectory tracking, while collision avoidance mechanisms ensure safe operations [238]. The continuous feedback and adaptation maintain accurate trajectory tracking [238]. By incorporating these steps and advancements, cooperative control enables drones to effectively work together, accomplish complex tasks, and achieve synchronized trajectory following [238,239,241]. This enhances efficiency and effectiveness in various applications, such as aerial formations, surveillance, and coordinated mapping missions. The cooperative control architecture for a UAV begins by collect sensory data and communicate with each other to exchange information. Tasks and roles are assigned based on mission requirements, considering capabilities and resource availability. Optimal paths and trajectories are generated to accomplish assigned tasks, considering the mission objectives and environmental constraints. The control layer translates high-level commands and planned paths into low-level actions, ensuring stability, motion control, and trajectory tracking. The mission management layer oversees the overall mission, adapting plans and allocating resources as needed based on real-time feedback from UAVs. This integrated approach enables efficient task allocation, precise control, and adaptive mission management, facilitating effective cooperation among the UAVs to accomplish complex objectives.

Fault-tolerant control (FTC) is a methodology employed to uphold acceptable performance and ensure the safety of a system even when faults or failures occur in its hardware or software components [242]. Such faults or failures may arise from diverse causes, including sensor malfunctions, actuator failures, communication losses, or software errors. The objective of fault-tolerant control is to detect faults or failures and mitigate their effects by reconfiguring the control system or adapting the control law. This can be accomplished through the utilization of redundancy, fault detection, and isolation (FDI) techniques [243–245], and fault accommodation strategies. Redundancy involves the presence of multiple copies of critical hardware or software components that can assume control in the event of a failure or fault. For instance, a UAV may possess redundant sensors or actuators that can be employed if the primary ones fail. FDI techniques employ sensor data to detect and isolate faults or failures in the UAV's hardware or software. FDI can be achieved using a variety of techniques, including observer-based approaches, statistical methods, or analytical redundancy. Fault accommodation strategies adapt the control law or reconfigure the control system to maintain the UAV's stability and performance in the presence of faults or failures. These strategies may involve switching to backup control law, adjusting control gains, or employing adaptive control techniques. Overall, fault-tolerant control plays a crucial role in ensuring the safe and reliable operation of UAVs even in the presence of faults or failures [242,246]. It enables UAVs to detect and mitigate the effects of faults or failures, allowing them to effectively continue operating and achieve their mission objectives. Recent advancements in the field of FTC for UAVs have been the subject of several studies. A survey article provides a comprehensive overview of recent research on fault diagnosis, FTC, and anomaly detection specifically tailored for UAVs [246]. Additionally, a separate review focuses on the topic of fault-tolerant cooperative control, specifically addressing the control of multiple UAVs in a fault-tolerant manner, this study delves into the recent developments in fault-tolerant cooperative control and offers a systematic analysis of FTCC methods applicable to multi-UAV scenarios. The study initially summarizes and analyzes the formation of control strategies for the fault-free flight conditions of multi-UAVs [239]. Furthermore, an adaptive fault-tolerant control method integrated with fast terminal sliding mode control (FTSMC) technology and a neural network is proposed for the attitude system of a quadrotor UAV in another study [247]. The utilization of the NN allows for the approximation of uncertain terms within the system, thereby enhancing fault-tolerant capabilities.

Prescribed performance control (PPC) is a control methodology specifically designed to fulfill prescribed performance criteria. In PPC, prescribed performance refers to ensuring that the tracking error converges to a predefined small residual set while satisfying a predetermined convergence rate and limiting the maximum overshoot to a sufficiently small constant, Consequently, the desired transient performance metrics, such as overshoot and convergence time, are successfully achieved [248]. This passage emphasizes the significance of achieving a good transient performance in aircraft control systems, encompassing traditional airplanes, hypersonic flight vehicles, and unmanned aerial vehicles (UAVs). It discusses several studies and methodologies that employ PPC to achieve this goal [248]. The study [249] focuses on the traditional PPC approach to develop an integrated guidance and control method for interceptors, ensuring excellent transient performance during target interception. In the case of hypersonic flight vehicles, studies [250,251] indicated that the normal PPC guarantees satisfactory transient performance. However, satisfying the strict initial condition for tracking error poses a challenge. To address this, modified versions of the PPC have been proposed [252] as non-affine models to reduce the reliance on the initial error. Nevertheless, these methods may result in a large overshoot due to the initial value selection of the performance function. To mitigate this issue, a newly designed performance function [253] is applied to develop a concise neural tracking controller for hyper-sonic flight vehicles. Simulation results demonstrate small or zero overshoot in velocity and altitude tracking. UAVs, which hold significant potential in military and civil applications, greatly benefit from good transient performance to effectively carry out tasks. Numerous tracking control methodologies utilizing PPC have been proposed. Ref. [254] presented a fuzzy-back-stepping-based tracking controller with prescribed performance for a single UAV. Additionally, PPC is applied to platoon control, leader–follower control, as well as decentralized, finite-time, adaptive fault-tolerant, synchronization control multi-UAVs [255] and quadrotor UAVs. In the backstepping-based study in [256], the simulation results validated their superior performance in achieving both transient and steady-state performance. In summary, this passage underscores the application of PPC in achieving a desirable transient performance across a range of aircraft, including airplanes, hypersonic flight vehicles, and UAVs. The referenced studies provide evidence of the effectiveness of PPC methodologies.

By extensively examining various literary sources, we derived Table 4, which outlines the pros and cons of each controller as per the opinions of different authors.

Table 4. Summarizing and comparing pros and cons: control techniques in the field of UAVs.

Control Technique	Advantage	Disadvantage
PID [27,94,203,211,217,218,257–260]	(1) Implementation is simple. (2) The reduction in steady state error can be achieved by increasing parameter gains. (3) It consumes minimal memory. (4) The design is user-friendly and it responds well.	(1) Conducting experiments can be a time-consuming process. (2) In certain cases, aggressive gain and overshooting may occur. (3) There is a possibility of overshoot occurrences when adjusting the parameters.
SMC [27,94,203,211,223,257,258,261,262]	(1) It exhibits high insensitivity to variations in parameters and disturbances. (2) It is capable of delivering significant implementation efforts. (3) Linearization of dynamics is not necessary for its operation. (4) It is efficient in terms of time. (5) Filtering techniques can be employed to reduce chattering effects.	(1) Severe chattering effects occur during switching. (2) The process of designing such a controller is intricate. (3) The sliding control scheme heavily depends on the sliding surface, and an incorrect design can result in unsatisfactory performance.

Table 4. *Cont.*

Control Technique	Advantage	Disadvantage
LQR [27,94,203,211,257, 258,263,264]	(1) Achieves robust stability while minimizing energy consumption. (2) Demonstrates computational efficiency. (3) The effectiveness of the system is enhanced by incorporating the Kalman filter.	(1) Complete access to the system states is necessary, but this is not always feasible. (2) There is no assurance regarding the speed of response. (3) It is not suitable for systems that demand a consistently minimal steady-state error.
Gain Scheduling [27,94,203,211,257, 258,265,266]	(1) Facilitates the rapid response of the controller to dynamic changes in operating conditions. (2) The design approach seamlessly integrates with the overall problem, even when dealing with challenging nonlinear problems.	(1) It is not time-efficient. (2) Gain scheduling heavily relies on conducting extensive simulations. (3) There are no guaranteed performance outcomes.
Backstepping [27,94,203,211,257, 258,267,268]	(1) Demonstrates robustness in the face of constant external disturbances. (2) Handles all states within the system and is capable of dealing with nonlinear systems.	(1) It is not efficient in terms of time. (2) It is sensitive to variations in parameters. (3) Implementation can be challenging.
H-Infinity [27,94,203,211,257, 258,264,268,269]	(1) Capable of operating in the presence of uncertainties within a system. (2) Complex control problems are addressed in two subsections: stability and performance. (3) Offers robust performance.	(1) Involves intricate mathematical algorithms. (2) Implementation can be challenging. (3) It necessitates a reasonably accurate model of the system to be controlled.
Adaptive control [27,94,203,208,209, 211,216,221,222, 257,258,270]	(1) Capable of handling systems with unpredictable parameter variations and disturbances. (2) Capable of handling unmodeled dynamics. (3) Exhibits rapid responsiveness to varying parameters.	(1) An accurate model of the system is necessary. (2) Implementing the design can be time-consuming. (3) It requires extensive design work before final implementations.
AI: Fuzzy Logic and Neural Network [27,94,203,211,213, 217,257,258,271–273]	(1) The control action is heavily influenced by the provided rules. (2) The controller can be manually prepared. (3) Capable of withstanding unknown disturbances. (4) Offers adaptive parameters for uncertain models. (5) The selected control system can be trained.	(1) Stability cannot be guaranteed. (2) Continuous tuning is necessary for critical systems. (3) It consumes a significant amount of computational power. (4) Offline learning may fail when uncertainties are present.

6.6. Considerations for Selecting an Appropriate Control Algorithm

Choosing the right control algorithm for a UAV is a crucial decision that depends on various factors, including the type of UAV, its mission objectives, environmental conditions, and available hardware and software resources. Several considerations should be taken into account when selecting or developing a control algorithm. Firstly, it is essential to identify the UAV's requirements. Understanding the UAV's performance requirements, such as flight range, payload capacity, and environmental conditions, is crucial in determining the most suitable control algorithm. Next, evaluate the different control algorithms available for UAVs, including classical PID, PID2, LQR, sliding mode control, and model reference adaptive controller. Assess the strengths and weaknesses of each algorithm and consider how well they align with the UAV's requirements. Consider the implementation complexity of the chosen control algorithm. Some algorithms may require significant computational resources or specialized hardware, such as ML-based algorithms or cooperative decision and control [225]. Select an algorithm that can be easily implemented on the UAV's hardware platform, considering the available computing resources. Once a control algorithm is chosen, optimize its performance by tuning its control parameters. Flight testing can be conducted to collect data on the UAV's flight behavior and adjust the control algorithm's parameters for optimal performance. Here are some key considerations when selecting or developing a control algorithm for a UAV [94,203,274]:

1. **Stability and control:** The algorithm should ensure the UAV's stability and controllability, even under turbulent or challenging conditions.
2. **Performance:** The algorithm should enable the UAV to achieve its performance objectives, such as speed, altitude, and maneuverability while minimizing power consumption and optimizing mission duration.
3. **Sensitivity to environment:** The algorithm should consider environmental factors that can affect the UAV's performance, such as wind, temperature, and humidity.
4. **Responsiveness:** The algorithm should be capable of responding quickly to changes in the UAV's mission objectives or unexpected events, such as obstacles or other aircraft.
5. **Computational requirements:** The algorithm should be computationally efficient and feasible for the available onboard processing hardware and software.
6. **Robustness:** The algorithm should be robust to uncertainties, such as sensor noise or errors in the UAV's kinematic model.
7. **Safety:** The algorithm should ensure that the UAV operates safely and avoids collisions with other objects, people, or animals.
8. **Regulatory compliance:** The algorithm should comply with local regulations and guidelines for UAV operations, such as flight altitude restrictions and flight path limitations.
9. **Human interaction:** The algorithm should enable human operators to interact with the UAV and provide inputs or commands, if necessary.

Overall, the technique for choosing the right control algorithm for a UAV involves the careful consideration of the UAV's requirements, the evaluation of different control algorithms, simulation and testing, implementation complexity, and optimization.

7. Fundamental Hardware/Software Architectures for UAVs: Applications and Issues

7.1. *The Hardware Architecture of UAVs*

The hardware architecture of unmanned aerial vehicles (UAVs) encompasses several critical components, such as the flight computer and controller, sensors, actuators, battery, communication interfaces, payload, and structural components. The flight computer and controller manage the flight path and stabilization of the UAV. Sensors provide crucial navigation, altitude, and orientation data, while actuators control the UAV's movement. The battery, chosen according to the application's requirements, powers the UAV. Communication interfaces enable remote control and data transmission, whereas the payload may include cameras, sensors, and other equipment specific to the application. Structural components, including the frame and arms, ensure support and stability for the UAV, allowing effective operation across applications. This hardware architecture significantly influences the capabilities and performance of UAVs across varying contexts [22,275–277]. Numerous studies have examined general hardware architecture. Multilevel architecture for UAVs has been proposed in the literature [22,275–277]. The characteristics of modern UAVs have been thoroughly discussed in [275,278]. The aspects of miniature UAVs are treated in [279], and the required software components for the real-time control implementation for UAVs are addressed in [199]. Regardless of scale, UAVs typically include the same components, with additions and modifications according to the application.

7.1.1. Flight Computer and Controller

The flight computer serves as the primary processing unit that governs the UAV's navigation and flight. It amalgamates data from all the sensors and actuators to manage the UAV's flight trajectory and stability. For medium- or large-scale UAVs, this unit is generally more advanced and potent, given the system's heightened complexity. A wealth of literature provides comprehensive reviews and surveys on flight controllers and computers [23,276,280,281]. Other works delve into the design and implementation of a UAV flight controller [282].

7.1.2. Sensors

The sensor suite of a UAV typically encompasses a range of devices such as accelerometers, gyroscopes, magnetometers, barometers, GPS, and cameras. These sensors offer crucial information regarding the UAV's orientation, position, and surrounding environment. Medium- or large-scale UAVs might additionally incorporate LIDAR [283], radar, and other specialized sensors for applications like navigation and mapping [158]. A brief comparison of remote-sensing platforms is presented in [284]. For agricultural applications, the sensors, and their deployment are discussed in [285,286], while their use in construction and civil applications is detailed in [99]. An examination of the electromagnetic interference on UAV sensors is covered in [287], and the application of different sensors in mining areas is discussed in [100]. Multi-sensor data fusion using deep learning (DL) for security and surveillance purposes is reviewed in [288], and remote sensing for forest health monitoring is explored in [289].

7.1.3. Actuators

This includes motors, servos, and electronic speed controllers (ESCs) that control the UAV's movement and stability. Medium- or large-scale UAVs are typically larger and more powerful to handle the increased weight and size of the UAV. The UAV electric propulsion system was reviewed in [105,290]. The application of the development of an actuator was analyzed in [291]. The development of other propulsion system plasma actuators was elaborated upon in [292].

7.1.4. Battery

This is the power source that provides energy to the UAV's components. A medium- or large-scale UAV typically requires a larger battery to provide enough energy to power its components, with many papers focused on UAV supply systems and the management of its energy [104]. While some [293] focused on the UAV architectures of power supply, their charging techniques are well discussed in [294], while the wireless charging of UAVs is covered in [295]. In addition, [296] presents the key technologies of the fuel cell of UAVs. The intelligent energy management and hybrid power supply for UAVs is reviewed in [297,298].

7.1.5. Communication Interfaces

This includes radios and other communication devices that enable the UAV to transmit data to and receive data from ground stations, other UAVs, or other devices. Medium- or large-scale UAVs are typically more sophisticated and capable of transmitting and receiving larger amounts of data over longer distances. The exploration of the characteristics of UAV communication network issues, design issues, and applications is reviewed in [29], whereas the used communication process for UAVs is discussed in [299]. A survey of networking and communication technologies is well presented in [300]. Fifth-generation (5G) systems and satellite communication for UAV navigation and surveillance are presented in [77]. Moreover, [124,301] performed an in-depth analysis of the swarm communication architectures. In addition, [302] describes UAV-based IoT communication networks and the applications for IoT for sustainable smart farming are explored in [303].

7.1.6. Payload

This is the equipment that the UAV is carrying for its specific mission, such as cameras, sensors, or other specialized equipment. A medium- or large-scale UAV is typically more sophisticated and specialized and may include specialized sensors, cameras, or other equipment to support its mission. Payload delivery UAV and dropping payload's capability are investigated, respectively, in [176,304].

7.1.7. Structural Components

These include the frame, arms, and other components that provide the UAV with its physical structure and support the other components. The structural components of a medium or large-scale UAV are typically larger, stronger, and more complex to support its size and weight. The concept and initial design of a UAV were addressed in [305]. And, UAV mechanical frame stress was analyzed by [306], while [307] reviewed the finite element methods for UAV structural analysis. A UAV wing's structural analysis and optimization was investigated by [308], and small-scale UAV structural design and optimization were elaborated on by [309,310].

This is a general hardware architecture for a UAV. Depending on the specific UAV and its mission, the architecture may vary, and additional components may be added to meet specific requirements. In some cases, UAVs may use internal combustion engines to generate electricity, which can be used to power the electric motors. However, this is relatively rare, as electric motors are typically more efficient, reliable, and environmentally friendly than internal combustion engines.

7.2. The Software Architecture for UAVs

It is a critical component that enables the UAV to operate effectively and efficiently. The UAVs' architecture, as an autonomous system, typically consists of several layers, including the firmware layer, operating system layer, middleware layer, and application layer [311–315]. The firmware layer includes the code that controls the hardware components of the UAV, such as the flight controller and sensors. The operating system layer provides the necessary interface between the firmware and higher-level software applications. The middleware layer includes software components that provide communication and data exchange between the different parts of the system. This layer includes protocols and software libraries for data transmission, processing, and storage. Finally, the application layer includes the software programs that run on top of the other layers and provide the necessary functionality for the UAV's intended application. This layer includes software for flight planning, navigation, data analysis, and payload control.

Overall, the software architecture for UAVs is a complex and highly integrated system that must be carefully designed to ensure the reliable and efficient operation in different applications. Advanced software techniques such as ML and AI are also becoming increasingly important in UAV software architectures to improve autonomy and decision-making capabilities.

7.3. UAV Applications and Main Issues

UAVs have numerous and diverse commercial, military, and scientific applications. The applications of UAVs have been discussed and categorized by numerous kinds of literature [49,315–318]. Some of the most common applications of UAVs include aerial photography and videography. UAVs can capture high-quality images and video footage from the air, making them ideal for applications such as film-making, real estate, and tourism. In agriculture [319], UAVs can be used to monitor crops, detect crop diseases, and optimize irrigation and fertilization, leading to more efficient and sustainable agriculture practices. UAVs can also be equipped with specialized sensors and cameras to aid in search and rescue operations, particularly in remote or hard-to-reach areas. In military and law enforcement, UAVs can be used for reconnaissance, surveillance, and target acquisition in military and law enforcement applications. UAVs find applications in infrastructure inspection [316,317], aiding in the efficient and cost-effective inspection and monitoring of structures such as bridges [320], pipelines, and power lines. They also significantly contribute to environmental conservation efforts by monitoring parameters such as air and water quality, as well as wildlife populations [41,43]. Furthermore, UAVs serve as essential tools in scientific research, facilitating environmental monitoring [321], atmospheric studies [37–42,161], and wildlife tracking. They have notably enhanced our understanding of cryospheric features, both on the surface and subsurface. UAVs have also revolutionized faunal studies by enabling non-invasive methods for the accurate counting and morphometric analysis of various animal species. Atmospheric surveys conducted by UAVs offer swift and versatile data collection, including aerosol sample collection. The design and development of specialized platforms, tailored to the challenging Antarctic environment, have been instrumental in the successful deployment of these applications [19]. Consumer UAVs are designed for personal use, such as hobbyist drones, aerial photography drones, and racing drones. Overall, the applications of UAVs continue to expand and evolve as new technologies and capabilities emerge, providing significant opportunities for innovation and advancement in a wide range of fields. Due to the increase in UAV applications, certain UAV uses are raising common concerns and issues across industries [29,322,323]. These include privacy concerns, regulatory compliance, technical challenges, specialized equipment requirements, and potential safety risks. Privacy concerns arise from capturing images and videos without consent, while regulatory compliance and technical challenges relate to operating UAVs in specialized environments. The need for specialized sensors and software, along with potential safety risks from accidents or crashes, are also common concerns for UAV use in different fields.

8. Key Trends: Open Source UAV Software and Hardware Projects

There are many open source projects related to the application of advanced control techniques in UAVs. A few examples are provided as follows.

8.1. PX4 Autopilot

Is an open source flight control platform [324] used for autonomous navigation and control applications, which supports a wide range of UAVs. The platform provides advanced control algorithms, such as model predictive control [219,220], adaptive control [216,221], and R [217,325], which can be used to improve the stability and performance of UAVs. This provides a flexible and modular platform for developing autonomous flight systems, including advanced navigation and control algorithms. The software is compatible with a range of hardware platforms and supports a variety of communication protocols.

8.2. ArduPilot

Is an open source autopilot platform [326] used for autonomous navigation and control applications, which supports a variety of UAVs, including fixed-wing aircraft, multi-rotors, and rovers. The platform provides advanced control algorithms, such as adaptive control and AI [222,270], that can be used to improve the stability and performance of UAVs [218]. It provides a range of features for autonomous navigation and control, including GPS waypoint navigation, automated takeoff and landing, and mission planning. The software is compatible with a wide range of hardware platforms and is actively maintained by a large community of developers.

8.3. TensorFlow for UAV

Is an open source project software library [327] for ML and AI applications. In the context of UAVs, TensorFlow can be used for a variety of applications, such as object detection and recognition, path planning and navigation [328,329], and sensor fusion. For example, TensorFlow can be used to train deep neural networks to recognize objects in images or videos captured by UAVs, which can be useful for applications such as search and rescue or surveillance. TensorFlow can also be used for path planning and navigation, by training ML models to predict the optimal trajectory for a UAV based on environmental and mission constraints. Additionally, TensorFlow can be used for sensor fusion, by integrating data from multiple sensors on a UAV to create a more accurate and complete picture of the environment.

8.4. Paparazzi UAV

This is an open source project [330] that provides a complete autopilot system for UAVs, including advanced control algorithms and tools for flight planning and mission execution [331,332].

8.5. Ground Control

QGroundControl [333], Mission Planner [334], APM Planner 2 [335], and UgCS [336] are open source ground control stations that provide a graphical user interface for controlling UAVs [337–339]. This platforms provides advanced control algorithms, such as adaptive control, that can be used to improve the stability and performance of UAVs.

8.6. AirSim

Aerial Informatics and Robotics Simulation [340] is an open source UAV simulator developed by Microsoft. It provides a realistic simulation environment for testing and developing UAV control algorithms, including the advanced physics-based modeling of the UAV and its environment [341–343]. The software is designed to be flexible and customizable, allowing users to experiment with different control strategies and sensor configurations. The platform provides advanced control algorithms, such as R, that can be used to improve the stability and performance of UAVs.

8.7. JdeRobot UAVs

Is an open source toolkit [344] for developing robotics including UAVs that provides a comprehensive set of tools and algorithms for controlling UAVs. The platform provides advanced control algorithms, such as model predictive control and R, that can be used to improve the stability and performance of UAVs [345,346].

8.8. DroneKit and DroneKit-Python

DroneKit and DroneKit-Python are open source SDK frameworks [347] for building apps that run on autopilot software such as ArduPilot and PX4. DroneKit provides a set of high-level APIs that allow developers to easily interact with the UAV autopilot system, access telemetry data, and send commands to the UAV, while DroneKit-Python [348] is a Python library that extends the capabilities of DroneKit and provides a simple and easy-to-use interface for developing Python-based UAV applications. This includes a number of high-level APIs for controlling and monitoring UAVs, as well as support for accessing sensor data, controlling actuators, and implementing custom behaviors. The advantages of DroneKit include its ability to support a wide range of development platforms, including Linux, Windows, and Mac OS X, and its flexibility in supporting multiple autopilot software platforms, including ArduPilot and PX4. This allows developers to build applications that can work with a wide range of UAV hardware and software configurations. Moreover, DroneKit provides a range of APIs for controlling and monitoring UAVs, including mission planning, telemetry, and vehicle control [349–351].

8.9. MAVLink

MAVLink is an open source lightweight communication protocol [352] widely used in the UAV industry to facilitate communication between the different components of a UAV system. Is designed to be platform-independent and can be implemented on a wide range of devices including ground control stations [353], onboard flight controllers, and other peripherals. MAVLink provides a flexible and extensible messaging system that allows the different components of a UAV system to exchange information such as flight status, sensor data, and control commands [354]. This enables the different components of a UAV system to work together in a coordinated and efficient manner. One of the key advantages of using MAVLink is its ability to support a wide range of hardware and software platforms. This allows UAV developers and manufacturers to leverage existing software and hardware components and build a system that meets their specific needs.

Another advantage of MAVLink is its ability to support multiple communication protocols including serial, UDP, and TCP. This flexibility makes it possible to use MAVLink in a wide range of applications [353–356] including ground control stations [353,354], autonomous vehicles, and remote sensing applications.

8.10. ROS for UAVs

The Robot Operating System (ROS) [357] is an open source software framework for robotics that offers developers libraries and tools to create and manage robotic systems. In the UAV field, ROS can be utilized to produce autonomous drones and other aerial robots. ROS finds applications in various areas in the UAV field, including navigation with SLAM [358] and path planning algorithms [359] to aid UAVs in navigating complex environments and avoiding obstacles. It also facilitates object detection [360–363], surveillance, and mapping. By integrating sensors like cameras, LIDAR, and GPS, ROS enables UAVs to perceive their surroundings and make intelligent decisions based on sensor data. Additionally, ROS provides a control framework with interfaces for motor control, communication with onboard sensors [364], and sensor data processing for decision making. Before deploying algorithms and control strategies in the real world, ROS offers a powerful simulation environment [360] for testing the functionality of UAVs. One of the significant advantages of using ROS in the UAV field is the large and active community that provides abundant resources, including libraries, tutorials, and forums, to support developers in building and deploying UAVs using ROS. Overall, ROS in the UAV field provides a powerful set of tools for developing autonomous drones and other aerial robots, enabling advanced navigation [365], perception, control, and swarm controller capabilities [361,366].

These projects are just a few examples of the many open source projects focused on the application of advanced control techniques in UAVs, such as Sparky2, CC3D, and Atom, ArduPilot Mega APM, FlyMaple, and Erle-Brain3. By utilizing these projects, researchers and developers gain access to cutting-edge tools and algorithms that can be used to develop advanced UAVs.

9. High-Level UAV Development Software and Categorization

High-level UAV development software refers to software that provide a user-friendly interface for developing, testing, and deploying control and navigation algorithms for UAVs. This type of software simplifies the process of developing and testing control algorithms by offering an abstract, high-level interface that does not require in-depth knowledge of the underlying hardware and software systems [350]. High-level UAV development software can be categorized into five main classes, as outlined below.

9.1. Simulation Software

Simulation software plays a crucial role in creating virtual environments for testing and evaluating UAVs, eliminating the need for physical prototypes. The simulation program offers accurate and plausible outcomes for financial system design prior to its actual implementation. Nevertheless, the simulation aspect may present certain obstacles that can impede the achievement of desired results if not adequately considered, such as the impact of disturbances like wind, abrupt weather changes, unexpected errors in the dynamic system, or any unforeseen circumstances. Some widely used simulation software tools in the UAV industry include gazebosim [367], AirSim [340], Webots [368], Morse [369], jMAVSim [324], New Paparazzi Simulator [370], HackflightSim [371], and Matlab UAV Toolbox [372]. The capabilities of each simulation software are differentiated below in Table 5 based on their advantages and disadvantages.

Table 5. Popular simulation software comparison pros and cons.

Simulation Software	Pros	Cons
UAV Toolbox MATLAB [372–375] PL: $MATLAB, Fortran, C++, C$ SOS: $Windows, Linux, MacOS$ L: $MasterLicenseGPCL$	• The most renowned and widely utilized software • Supports complex simulations • User-friendly Equipped with readily available toolboxes and tools. • The most prevalent software mentioned in research papers.	• Occasionally resource-intensive and time-consuming.
GazeBoSim [367,376,377] PL: $C++$ SOS: $Linux, MacOS$ L: $ApacheV2.0$	• Highly realistic simulation environment with GUI • Open source and extensible • Wide range of sensor support • Integration with ROS	• Steep learning curve • Resource intensive • Limited real-world dynamics • Occasional stability issues (unreasonable robot jumps occur in collision)
AirSim [156,340–343] PL: $C++$ SOS: $Windows, Linux$ L: MIT	• High-fidelity simulation environment offers accurate physics modeling • Multi-vehicle and sensor support • Ability of integration with popular frameworks	• Computationally demanding • Occasional stability bugs (sensor synchronization, communication errors)

PL: programming language, **SOS:** supported operating system, **L:** license (default).

9.2. Flight Control Software

Flight control software is responsible for managing UAV flight operations and onboard systems, including cameras and sensors. Prominent flight control software platforms include ArduPilot [326], PX4 [324], Paparazzi [330], Multiwii series [378], Cleanflight [379], Betaflight [380], INAV [381]), and OpenPilot series [382] (LibrePilot [383], dRonin [384]).

9.3. Ground Control Software

Ground control software enables the remote monitoring and control of UAVs. This provides operators with telemetry data, waypoint setting capabilities, and flight control options. Popular ground control software platforms include Ardupilot Mission Planner [334,335], QGroundControl [333], and UgCS [336].

9.4. Computer Vision Software

Computer vision software plays a vital role in processing and analyzing images and videos captured by UAVs. It is extensively used in applications like aerial mapping, surveying, and inspection. Well-known computer vision software tools in the UAV industry include OpenCV [385], TensorFlow [327], and PyTorch [386].

9.5. Sensor Integration Software

Sensor integration software facilitates the integration of various sensors and systems into UAV platforms. It enables the seamless integration of sensors such as LiDAR, thermal cameras, and multispectral cameras. Prominent sensor integration software tools in the UAV industry include ROS [357] and MAVLink [352]. These examples represent a fraction of the UAV development software tools commonly employed in the industry. Numerous other specialized software tools are available for specific applications and use cases. The open source nature of many of these tools fostered the rapid advancement of UAV technology and the flourishing of the industry.

10. Open Issues and Future Research Directions for UAVs

10.1. Open Issues

The field of UAVs presents several open issues that researchers are currently grappling with. These issues encompass limitations in operability, including flight autonomy, path planning, battery endurance, flight time, and limited payload carrying capability [50]. Another significant challenge lies in the integration of UAVs within the relief chain to address the specific obstacles faced by international humanitarian organizations (IHOs) [387].

Deploying UAV swarms in diverse environments introduces various hurdles, such as decision making, control, path planning, communication, monitoring, tracking, targeting, collision, and obstacle avoidance [122–124,127]. Additionally, concerns surrounding safety, privacy, security, and power in unmanned systems contribute to existing challenges. For example, the absence of GPS alerts about the surrounding areas poses potential safety risks, while privacy concerns arise from the collection of personal data by UAVs. The vulnerability of UAV signals to hacking or jamming attempts also represents a security challenge [50]. Other challenges in UAVs can be summarized in ensuring the security of sensitive data, as the lack of encryption exposes UAVs to risks of data hijacking and potential threats of data leakage [50,388].

Moreover, the need for longer flight times to achieve a greater economic impact presents a power-related challenge [50]. Additionally, the lack of standardization in UAV operations hinders their widespread use. Ambiguity and the absence of significant standards and regulations affect various aspects such as airspace regulations, weight and size limits, privacy considerations, and safety requirements [50,388]. Utilizing wireless sensors is crucial for enabling smart traffic control systems and enhancing UAV performance [388]. UAVs face limitations in the transmission range, processing capability, and speed. Addressing these limitations requires research contributions to advance UAV technology [388]. Resource allocation poses a challenge in terms of optimizing UAV path planning and resource allocation to enhance operational efficiency and performance [388]. Speed limitations can be overcome by regulatory bodies allowing UAVs to operate at higher altitudes [388]. Power limitations and battery life are critical challenges that need to be addressed to improve UAV operations. This includes addressing energy consumption, extending battery life, and developing efficient recharging methods [389]. Furthermore, ref. [390] identifies several challenges and problems, including social perception concerns, privacy and safety concerns, and environmental concerns. However, the major challenge in the UAV field is communication, which can be addressed by advancements in microprocessors to enable the intelligent autonomous control of various systems. Drones possess distinguished features such as dynamic node mobility and network topology, variable network performance, flight range, autonomous and remote operations, fast data delivery, and cost-effectiveness [391]. We classified the open issues of UAVs into different categories, as shown in Figure 4. These categories encompass challenges related to operability, technology, regulatory aspects, safety, privacy, and security. It is important to note that there may be overlaps between these classes, as certain research directions can have implications across multiple categories. Additionally, this classification is not exhaustive, and there could be alternative classifications based on different perspectives or viewpoints.

10.2. Future Research Directions

The field of UAVs is witnessing future research trends that encompass various areas. One prominent area is swarm UAV systems, where multiple drones collaborate to achieve common goals across various applications, such as military reconnaissance and precision agriculture. Resource allocation, obstacle avoidance, tracking, path planning, and battery scheduling in swarm UAV systems are greatly influenced by machine learning and deep learning algorithms. These algorithms contribute to the development of smaller, lighter, and smarter nano UAVs [144,392].

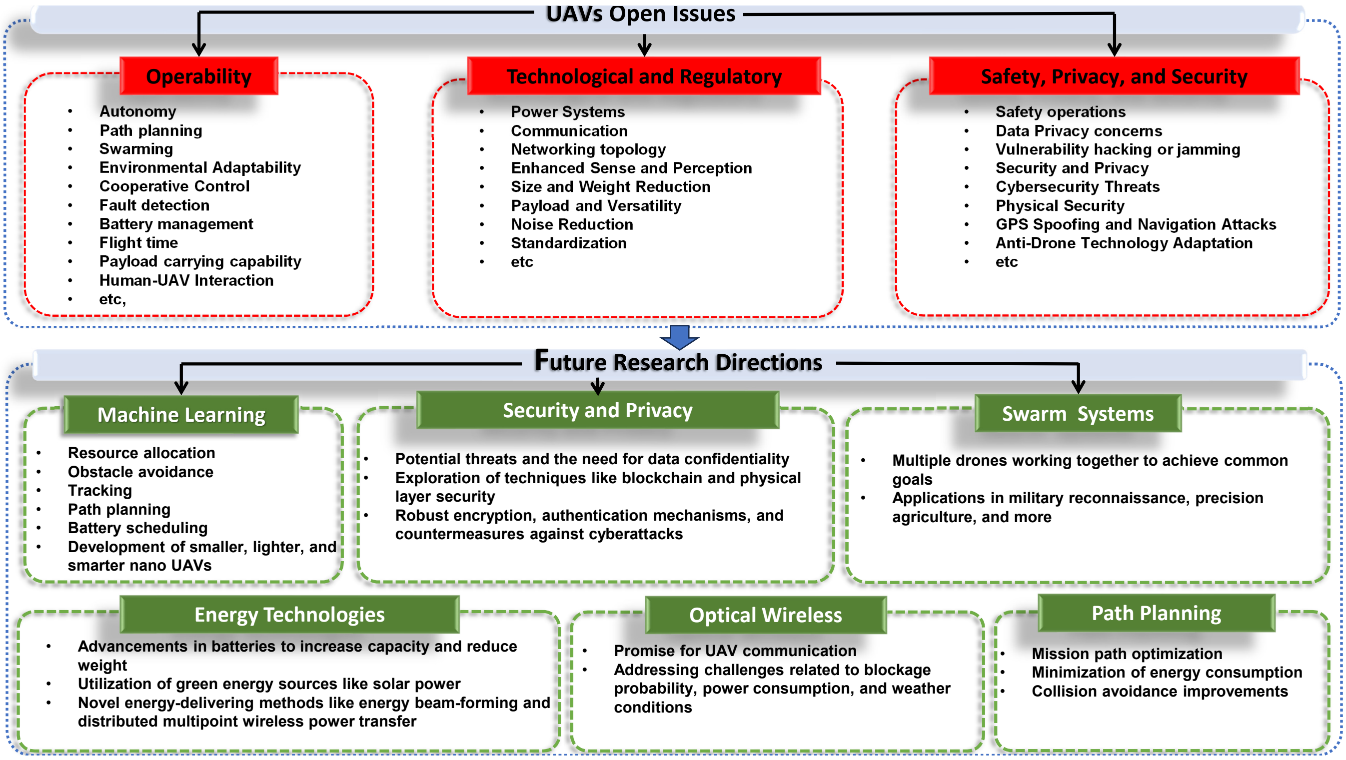


Figure 4. Open issues and future research directions in the field of UAVs.

Security and privacy are critical considerations in UAV systems, given the potential threats and the need to safeguard data confidentiality. Further research is required to explore techniques such as blockchain and physical layer security to effectively address these concerns [393,394]. Additionally, trajectory and path planning techniques should be improved to optimize mission paths, minimize energy consumption, and ensure collision avoidance.

Advancements in energy charging technologies are vital to enhance the UAV performance. This includes developing enhanced batteries and utilizing green energy sources like solar power to extend flight times. Novel energy-delivering methods such as energy beam-forming and distributed multipoint wireless power transfer (WPT) can also enhance the charging efficiency.

Optical wireless communications (OWCs) hold promise for UAV communication. However, challenges related to blockage probability, power consumption, and weather conditions need to be addressed to ensure reliable and efficient communication in UAV systems [392].

To enhance the overall UAV performance, several recommendations can be implemented. Firstly, advancing battery technologies to increase capacity and reduce weight, along with the adoption of efficient charging techniques such as wireless or solar power, would significantly benefit UAV operations. Secondly, collision avoidance systems can be improved through the development of advanced algorithms and sensor technologies. Artificial intelligence and machine learning can be utilized for autonomous decision making in collision avoidance scenarios. Thirdly, the security of UAV systems should be strengthened through the implementation of robust encryption, authentication mechanisms, and effective countermeasures against cyberattacks. Lastly, it is crucial to establish clear and comprehensive regulations for UAV operation, including guidelines for autonomous UAV swarms. These regulations should address safety, privacy, and environmental considerations to ensure responsible and sustainable UAV deployment [18,50,392].

11. Conclusions

In conclusion, this paper presents a comprehensive and in-depth analysis of UAV development, covering various research directions in the last three years, potential open development axes, aircraft control development axes, hardware and software architectures, applications, and key trends in the field. Through the use of Scopus database and expert analysis, this paper sheds light on recent UAV research trends and the interactions among them. Furthermore, this paper highlights the integration of cutting-edge technologies such as AI, communications, IoTs, aircraft detection, control and autonomous flight, perception and sensing, environmental monitoring and conservation, miniaturization, swarming and cooperative control, and transformability capability as potential open development axes in UAVs. It also discusses classical, modern, intelligent, and adaptive control techniques, pushing the boundaries of UAV control with advanced trends, and the importance of selecting appropriate control algorithms. The paper also provides insights into the fundamental hardware and software architectures of UAVs, including flight computers and controllers, sensors, actuators, batteries, communication interfaces, payloads, and structural components. It discusses the diverse applications of UAVs and their main issues, as well as key trends in open source UAV software and hardware projects. In conclusion, this review paper serves as a valuable resource for researchers, developers, and practitioners interested in staying updated with the latest advancements in UAV development and research trends. It provides a comprehensive overview of key aspects of UAV development, identifies potential open development axes, discusses aircraft control development axes, and explores the diverse applications and main issues in the field. With its comprehensive analysis and insights, this paper makes an indispensable contribution to the scientific literature on UAVs, providing valuable guidance for future research and development in this dynamic field.

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