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Review Article

Unmanned Aerial Vehicles (UAVs), the New Actors of War: Historical Development, Current Status and Future

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ABSTRACT

This study aims to examine the historical development of unmanned aerial vehicles (UAVs) in the military domain, identify key milestones and operational roles throughout this process, analyze the technical and operational challenges encountered, and provide solution proposals along with evaluations of potential future roles based on recent technological advancements. Accordingly, a systematic literature review method was adopted. Using predefined search criteria, 236 documents were retrieved from the Google Scholar database, and relevant sources were selected and analyzed based on inclusion and exclusion criteria. The findings reveal that UAVs were initially used as targets in the early 1900s and gradually evolved to fulfill roles in reconnaissance, surveillance, combat, electronic warfare, and logistical support. Major challenges identified include limited battery capacity, insufficient collision avoidance, cybersecurity vulnerabilities, and payload constraints. It is concluded that wireless power transfer, artificial intelligence, and swarm technologies will play a critical role in shaping the future of military UAVs.

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1. Introduction

Technological progress has continuously redefined the character of warfare, from traditional methods involving close combat and mechanical weaponry to modern, technology-driven confrontations. As warfare transitions from manpower-intensive to technology-centric paradigms, unmanned aerial vehicles (UAVs) have emerged as transformative assets in military operations (Erdağ, 2020). Just as gunpowder revolutionized warfare by replacing swords and shields, UAVs now represent a new era of combat, significantly altering modern military doctrines and

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strategies. Their increasing prevalence in conflict zones has led many scholars to identify UAVs as a defining element of contemporary warfare (Kasapoğlu & Kırdemir, 2018). UAVs are aircraft systems that operate without an onboard human pilot. These systems can perform missions with lethal or non-lethal payloads, reduce risks to human life, and offer cost advantages over traditional manned aircraft (Sadraey, 2020). They can be remotely controlled via ground stations or programmed to fly autonomously using onboard sensors and autopilot technologies (Elmeseiry, Alshaer & Ismail, 2021). In academic and professional literature, UAVs are also referred to as drones, remotely piloted aircraft (RPA), or unmanned aerial systems (UAS) (Giordan et al., 2020). Although UAVs are widely known for their military use, they also serve diverse civilian sectors including agriculture, logistics, environmental monitoring, emergency response, telecommunications, and smart city applications (Chamola et al., 2021; Laghari et al., 2023).

UAVs are categorized based on several parameters. By weight, they are classified as Nano, Micro, Small, Medium, and Large; by altitude and range, as Handheld, Close, Tactical, MALE (Medium Altitude Long Endurance), HALE (High Altitude Long Endurance), and Hypersonic. Usage-based classifications include Personal, Commercial, Governmental, and Military. Military UAVs can also be distinguished by payload (armed vs. unarmed) and operational role (reconnaissance, combat, target simulation, logistics) (Akyürek, Yılmaz & Taşkıran, 2012; Chamola et al., 2021; Villi & Yakar, 2022). Further classifications, Class 1 (<150 kg), Class 2 (150–600 kg), and Class 3 (>600 kg), are also used in regulatory and operational contexts (Atasoy, 2022).

The military roots of UAVs date back over 150 years. In 1849, the Austrians used bomb-laden balloons to attack Venice (Kozera, 2018). UAVs in their modern form began appearing in World War I, with continued development through World War II. A significant milestone occurred in 1970 when the American BGM-34A became the first UAV to successfully fire a guided air-to-surface missile (Chamola et al., 2021). In subsequent decades, UAVs evolved from decoy and reconnaissance roles to full-scale offensive and surveillance functions. The 1990s marked increased R&D investment, especially in the U.S. and Israel, leading to widespread adoption of UAVs in combat operations (Glade, 2000; Karaağaç, 2014).

Today, UAVs are used for a wide array of military tasks including target tracking, electronic warfare, rescue operations, and precision strikes. Their ability to operate in high-risk environments without endangering personnel underscores their strategic value (Atasoy, 2022). However, several technical and operational challenges persist. Vulnerabilities have been identified even in advanced UAV systems used for critical missions, including weaknesses in communication security, susceptibility to hacking, and limitations due to battery life and weather conditions (Chamola et al., 2021; Rodday et al., 2016). These issues may hinder the performance and deployment of UAVs in complex scenarios. Despite these limitations, emerging technologies offer promising solutions. Innovations in artificial intelligence, machine learning, 5G communication, and the Internet of Things are expected to enhance UAV autonomy, coordination, decision-making, and operational resilience (Elmeseiry, Alshaer & Ismail, 2021). Given these trends, this study aims to examine the historical development of UAVs in military contexts, analyze their current roles and limitations, and explore the transformative potential of emerging technologies. The research aims to contribute to a clearer understanding of how UAVs are reshaping and will continue to reshape the future of warfare. In this context, the current study makes an original contribution by integrating the historical development, current challenges, and future technological directions of UAVs into a single systematic literature review framework, thus offering a comprehensive perspective for both academics and practitioners. Accordingly, the research problems are identified as follows:

What is the historical development process of UAVs? What are their roles in the military field?

1. What are the challenges/problems faced by UAVs? What solutions are proposed against these challenges?
2. What are the developments that will affect UAVs? How might UAVs be shaped in the future in light of these developments?

2. Methodology

In this study, the systematic review method was used to answer the research questions (Karaçam, 2013). A systematic literature review is defined as “a means of evaluating and interpreting all available research on a specific definition as a guide for the study” (Kitchenham, 2004). Accordingly, the study followed the planning, execution, and reporting stages of the systematic review process (Kitchenham, 2004; Özmen & Karamustafaoğlu, 2019). During the planning and execution phases, the research problem and sub-problems were clearly defined, and the purpose of the review was established. Inclusion and exclusion criteria were developed to ensure that selected research materials aligned with the study’s objectives (Table 1). Search terms included the Turkish keywords "insansız hava araçları", "askeri" and "savunma sanayi", along with the English terms "military unmanned aerial vehicles" and "recent" (Table 2). The search was conducted via Google Scholar, using databases such as SCI, SSCI, Scopus, ERIC, and EBSCO, where open access was available. All documents (articles/papers/theses/books etc.) containing the keywords in their titles were included in the scan.

Table 1. Inclusion and exclusion criteria of the study

Inclusion criteria	Exclusion criteria
Papers included range from 2010–2023	Repeated documents
Fully accessed refereed article/paper/book/ thesis	Studies examining other areas of use outside the military domain
UAV activities in the military field	Studies not published in peer-reviewed journals
Studies examining the latest developments in UAVs	Studies without full-text availability
Studies examining UAVs in general	Studies published in other languages
Studies in Turkish and English	

Table 2. Literature search terms and number of documents accessed

Search terms	Intended use	Number of documents
All in title: military "unmanned aerial vehicles"	Reaching UAV research in the military field	110
All in title: recent "unmanned aerial vehicles"	Examining the latest developments in UAVs	30
All in title "unmanned aerial vehicles"	Accessing Turkish documents on UAVs	96

The exclusion criteria were defined as follows: (i) repeated documents, (ii) studies examining other areas of use outside the military domain, (iii) studies not published in peer-reviewed journals, (iv) studies without full-text availability, and (v) studies published in other languages. The Turkish literature search was conducted exclusively using the term ‘İHA,’ and the scope of the study was limited to this term. The term ‘drone’ was not included because it is a very broad and general concept, which could significantly expand the search to include studies outside the intended focus on military UAV applications. This approach preserves the rigor and defined scope of the review, while acknowledging the exclusion of broader terms as a limitation for future research. Some studies identified during the review were excluded based on the predetermined criteria. The remaining documents were analyzed to address the research questions. All selected sources were examined in detail to explore the historical development, military applications, current challenges, and potential future advancements of UAVs, along with related recommendations. In this way, a thorough and comprehensive literature review was carried out. In total, 236 documents were initially retrieved. Based on the inclusion and exclusion criteria, 135 documents were excluded, and 101 studies were finally included in the review.

3. Results and Discussion

The findings obtained in this study and the discussion of the findings are presented according to the research problems.

3.1. What is the Historical Development Process of UAVs? What are their Roles in the Military Field?

The emergence of unmanned combat vehicles is rooted in tactical innovations rather than technological breakthroughs. In the 16th century, explosive-laden unmanned boats were used against enemy fleets (Kozera, 2018). The first known UAV use dates back to 1849, when the Austrian army attacked Venice using 200 bomb-laden balloons. Although affected by adverse winds, this incident is considered the first drone attack in history (Udeanu, Dobrescu & Oltean, 2016). Some sources also mention the use of balloons for reconnaissance during the American Civil War in 1793 (Gürboğa, 2023). The modern UAV concept began during World War I with attempts to build pilotless aircraft for target practice. Notable among these were the radio-guided Aerial Target Missile developed by M. Low in 1914 and the "Hewitt-Sperry Autoplane" in 1916, which achieved stable autopilot flight (Katrancı, 2020; Keane & Carr, 2013). These efforts laid the groundwork for today's cruise missiles (Udeanu, Dobrescu & Oltean, 2016). The 1930s saw the emergence of reusable UAVs, such as the British "Queen Bee", considered the precursor of modern target drones. The Cold War era catalyzed further UAV development. In the 1960s, after the U2 incident, the U.S. initiated the Ryan 147 AQM-34 "Lightning Bug" program, conducting over 3,000 missions during the Vietnam War (Kozera, 2018; Shaw, 2016). Ryan Model 147 is widely recognized as the first UAV meeting modern definitions (Zaloga, 2011). Israel’s contributions during the 1973 Yom Kippur War, such as using UAVs to deceive enemy defenses and developing the IAI Scout with real-time surveillance capabilities, were pivotal (Yuval, 2011).

The 1980s expanded UAV roles to include missile guidance and decoy missions. In 1982, Israel successfully used UAVs against Syrian air defenses in Lebanon (Kozera, 2018). The 1990s saw the rise of armed UAVs; the US-Israel-developed AAI Pioneer was used in the Gulf War, while the MQ-1 Predator evolved from reconnaissance to armed capabilities with the addition of AGM-114 Hellfire missiles (Karaağaç, 2014; Katrancı, 2020). Between 2002 and 2005, the EU led the CAPECON project for UAV development. By 2012, the US had 7,494 UAVs in its arsenal. By 2013, over 50 countries, including China, Iran, Israel, Pakistan, and Turkey, were actively developing UAV technologies (Karaağaç, 2014).

In Turkey, UAV interest began in the 1980s with the Banshee target drone. The first indigenous prototype, UAV-X1 Şahit, was developed by TAI in 1990. This was followed by Turna (1995) and Keklik (2001) for training purposes (Atasoy, 2022). Between 2000 and 2010, mini and tactical UAVs entered the Turkish Armed Forces (TAF) inventory. Anka-S, first flown in 2016, entered service in 2018 and became armed by 2017. Bayraktar TB2 joined the inventory in 2014 and began firing trials in 2015 with MAM-L munitions (Mevlütoğlu, 2020). Both platforms have been extensively used in counter-terrorism operations. In 2019, TAI introduced Aksungur, capable of long-endurance attack and surveillance missions. Vestel Defense's Karayel-Su and Baykar Defense's Bayraktar Akıncı followed, the latter capable of carrying F-16 class munitions and performing high-altitude, long-endurance missions (Atasoy, 2022). Bayraktar TB2 played a critical role in Azerbaijan's success during the 2020 Nagorno-Karabakh war. Globally, the U.S. leads in UAV technology with platforms like the MQ-9 Reaper, followed by Israel with its Heron series. China and Russia have also advanced significantly. Turkey has emerged as one of the few countries producing MALE, mini, and loitering munition UAVs, with platforms like ANKA-S, Bayraktar TB2, and Karayel (Karaağaç, 2016).

UAVs, which began as simple decoys, have evolved into sophisticated combat systems. Initially limited to reconnaissance, they now play active roles in modern warfare thanks to their ability to carry precision-guided munitions (Çağlar & Gülmez, 2023). In the literature, military UAVs are divided into three categories according to their missions (Korkmaz, İyibilgin & Fındık, 2016).

- Target and decoy: Aids in target designation, used as decoys against enemy air defense or fighter aircraft
- Reconnaissance and surveillance: Vehicles that gather information about the enemy through reconnaissance and surveillance
- Conflict capable of attack

Considering their historical development and current military use, UAVs play key roles in surveillance, reconnaissance, target detection, tracking, combat, electronic warfare, search and rescue, and logistics (Atasoy, 2022; Ekmekçioğlu & Yıldız, 2018; Kozera, 2018;). UAVs are effective and safe in 4D environments, dull, dirty, dangerous, and deep, where manned aircraft may face risks (Korkmaz, 2020; Atasoy, 2022). The Undersecretariat for Defence Industries classified military UAV missions into five categories: reconnaissance/surveillance support, attack, target simulation, electronic warfare, and special operations (SSM, 2011).

3.2. What are the Challenges/Problems Faced by UAVs? What Solutions are Proposed against these Challenges?

Although UAVs are experiencing great development with the impact of developing technology, it is a fact that they face some challenges brought by technology and that these problems will continue to change in the future. In this study, the documents accessed were analyzed and codes were created under the themes of "*technical and operational challenges*" and "*security and communication challenges*" for the challenges/problems encountered by

UAVs (Table 3). Through these codes, it was tried to include the challenges faced by UAVs and solution suggestions.

Table 3. Challenges/problems faced by UAVs

Theme	Codes	References
Technical and Operational Challenges	Battery capacity challenge	(Elmeseiry, Alshaer & Ismail, 2021; Lee & Yu, 2017; Mahesh, Chokkalingam & Mihet-Popa, 2021; Michini, et al. 2011; Mohsan et al., 2023; Rong et al., 2023)
	Difficulty sensing and avoiding collisions	(Chen, González-Prelcic & Heath, 2020; Doğan, 2019; Lin & Saripalli, 2017; Vinokursky, Mezentceva & Samoylov, 2020; Wei et al., 2021)
	Limited load capacity	(Griffiths et al., 2007; Karaağaç, 2014; Katrancı, 2020; Mohsan et al. 2022; Mohsan et al., 2023
	Difficulty working in adverse weather conditions	(Akyürek, Yılmaz & Taşkıran, 2012; Doğan, 2019; Karataş, 2020; Mohsan et al., 2023)
	Inadequate defense against external physical influences	Akyürek, Yılmaz & Taşkıran, 2012; Korkmaz, İyibilgin & Fındık, 2016; Lyu & Zhan, 2022)
	Difficulty reaching high speed	(Doğan, 2019; Dikmen, 2015; Karaağaç, 2014; Mohsan et al., 2023)
Security and Communication Challenges	Cyber security/data security problem	(Akyürek, Yılmaz & Taşkıran, 2012; Mohsan et al., 2023; Shafik, Matinkhah & Shokoor, 2023; Tsao, Girdler & Vassilakis, 2022; Tlili et al., 2022)
	Data link dependency and communication challenges	(Karatas, 2020; Katranci, 2020; Khan et al., 2021; Mohsan et al., 2023)

3.2.1. Battery capacity challenge

The limited battery capacity of UAVs is a major challenge affecting their flight time and mission range (Elmeseiry, Alshaer & Ismail, 2021). Increasing battery capacity adds weight, which negatively impacts UAV performance. Due to limited energy storage, UAVs can only operate for limited periods. To address this, three main approaches have been proposed in the literature:

1. *Effective battery management:* This includes planning, scheduling, and replacing batteries to ensure UAVs complete their missions (Elmeseiry, Alshaer & Ismail, 2021). Saha et al. (2011) developed a battery charge prediction model to forecast when battery power will deplete, enabling better battery assignment and planning. Heuristic algorithms based on charge and discharge timings are used to optimize battery management (Elmeseiry, Alshaer & Ismail, 2021). Additionally, hot-swappable battery systems allow batteries to be replaced while the UAV remains connected to an external power source, preventing data loss and minimizing downtime (Michini et al., 2011).

2. *Using solar energy:* Solar energy supports high-altitude, long-duration flights by serving as the primary power source for propulsion. Batteries act as secondary sources during nighttime or low sunlight conditions (Lee & Yu, 2017).

3. *Wireless power transfer (WPT):* WPT technology is proposed as a flexible solution requiring no precise positioning, making it ideal for charging UAVs (Mahesh, Chokkalingam & Mihet-Popa, 2021). Charging from power lines during missions has been discussed (Simic, Bil & Vojisavljevic, 2015). Another proposal includes automatic charging stations placed along UAV flight paths, comprising solar panels, wireless charging pads, batteries, and power converters (Elmeseiry, Alshaer & Ismail, 2021).

3.2.2. Difficulty sensing and avoiding collisions

Collision avoidance is a critical challenge for UAVs, which may collide with static or dynamic obstacles during missions (Lin & Saripalli, 2017). UAV collision avoidance systems typically include three steps: obstacle detection, collision prediction, and avoidance (Wei et al., 2021). Initially, UAVs use sensors to detect the environment and gather information about the identity, position, and velocity of nearby obstacles. Then, using this data, UAVs predict whether a collision is likely and, if so, plan an evasive path (Wei et al., 2021). Several difficulties hinder effective collision avoidance. First, UAVs operate in 3D space, making their trajectories more complex than those of ground vehicles. This spatial complexity complicates algorithm design. Second, UAVs may face a wide variety of obstacles, including stationary objects like buildings and trees, and moving ones such as birds or other aircraft. Finally, many obstacles are dynamic, requiring real-time prediction and rapid response.

The literature presents different classifications for collision prediction methods (Elmeseiry, Alshaer & Ismail, 2021; Lin & Saripalli, 2017). Wei et al. (2021) classified prediction approaches into trajectory fitting and machine learning methods. Trajectory fitting methods use mathematical models, such as least squares fitting, to estimate future trajectories (Vinokursky, Mezentceva & Samoylov, 2020). Machine learning methods learn motion patterns from past data to predict trajectories or collision probabilities (Chen, González-Prelcic & Heath, 2020). These methods are often better suited for UAVs due to their ability to handle nonlinear and complex environments.

3.2.3. Cyber security/data security problem

With the rapid advancement of UAV technology, ensuring the security and integrity of these systems has become critically important. UAVs are vulnerable to cyber-attacks such as unauthorized access, system manipulation, and data breaches, posing significant security risks (Shafik, Matinkhah & Shokoor, 2023). Attacks like signal spoofing, GPS jamming, and hacking can cause UAV malfunctions and even lead to fatal outcomes (Elmeseiry, Alshaer & Ismail, 2021). GPS jamming involves injecting false signals to mislead UAV navigation, and attackers may gain full control by inserting unauthorized commands. Similarly, session hijacking can severely disrupt communication links. In military operations, UAVs face threats like data leakage and can be exploited for illegal activities such as data theft, privacy invasion, or smuggling (Tlili et al., 2022). Moreover, attackers may overload networks by sending excessive requests, leading to communication disruptions, processing unit strain, and battery drainage (Mohsan et al., 2023). Protecting UAVs against cyber threats is essential for maintaining operational security and data integrity. The literature proposes several countermeasures:

- Current algorithms focus mainly on single UAV networks; however, enhanced or modified algorithms are needed for multi-UAV systems (Tsao, Girdler & Vassilakis, 2022).
- Most security analyses overlook software and hardware variations across different UAV types. A unified security framework applicable to various UAV systems is necessary (Mohsan et al., 2023).
- Flight control computer attacks can alter mission parameters and disrupt operations. Built-in hardware/software tools like alert generation, controller prediction, and real-time monitoring can mitigate such threats (Mohsan et al., 2023).

- Shafik et al. (2023) recommend strong encryption, secure communication protocols, robust firmware, physical protection measures, cybersecurity integration, and mitigation of insider threats.

These strategies play a vital role in enhancing the resilience of UAVs against evolving cyber threats.

3.2.4. Limited load capacity

Payload refers to the capacity of a UAV (Unmanned Aerial Vehicle) to carry a load, which can range from a few grams to several thousand kilograms. However, a larger payload typically results in shorter flight times, higher battery consumption, and increased size. Thus, limited payload capacity remains one of the major challenges for UAVs. Onboard payloads such as digital, stereo vision, and thermal cameras can restrict the ability to carry additional sensors like temperature, GPS, or gate detection modules. Moreover, integrating heavier sensors such as laser scanners, ultrasonics, RADAR, and LIDAR further strains the payload capacity (Griffiths et al., 2007). While heavy payloads tend to reduce flight duration, UAVs with larger surface areas and multiple engines can store more power, helping to extend flight time. Therefore, high-quality payload systems, when properly optimized, can support longer flights without compromising accuracy and resolution (Mohsan et al., 2022). In military applications, the use of armed UAVs has increased the demand for greater payload capacity. The presence of bombs, missiles, and their deployment systems emphasizes the critical role of payload in the effectiveness of armed UAVs (Akyürek, Yılmaz & Taşkın, 2012).

3.2.5. Difficulty working in adverse weather conditions

In adverse weather conditions such as storms, rain and wind, it is difficult to deploy UAVs for precision applications due to unwanted deviations from predetermined trajectories (Karataş, 2020). Weather conditions also affect the operation time, path altitude, UAV altitude and flight direction. In natural disaster conditions such as typhoons, hurricanes or tsunamis, atmospheric conditions pose a fundamental challenge for UAV missions. In these conditions, it is very difficult for UAVs to hover, read accurate data and operate. Therefore, the dependence of UAVs on meteorological conditions creates a sensitivity for these systems and constitutes one of the negative factors for them (Doğan, 2019). According to Mohsan et al. (2023), it is necessary to focus UAV research on technical features and UAV capabilities that can withstand adverse weather conditions and complete weather-sensitive missions efficiently and safely.

3.2.6. Difficulty reaching high speeds

The slower speed of UAVs compared to manned combat aircraft is one of the most important concerns for this technology, which requires further research and investigation (Mohsan et al., 2022; 2023). This speed problem of UAVs leads to the preference for the use of manned systems in situations that require fast maneuvering and immediate response. UAVs with lower speed performance are slow in terms of gathering information in dangerous areas and being exposed to enemy fire. This issue becomes more critical when combined with the fact that unmanned vehicles lack the ability to protect themselves from enemy defenses compared to manned aircraft (Doğan, 2019). Today, the development of new systems that will reach hypersonic speed for UAVs has become the focus of today's R&D studies and researchers (Akyürek, Yılmaz & Taşkıran, 2012). Considering that hypersonic speed corresponds to 6120 km per hour, it can be said that hypersonic UAVs will be revolutionary. With the development of these systems, targets at very long distances will be reached and destroyed within minutes.

3.2.7. Inadequate defense against external physical influences

Unarmed UAVs have no defense capability. UCAVs are more vulnerable to air attacks and defense systems than manned aircraft. This is because their threat detection capability is weaker than a live pilot (Korkmaz, İyibilgin & Fındık, 2016). The fact that the weapon systems of enemy elements pose a threat to UCAVs requires UCAVs to have advanced technological features. High speed and altitude power, payload carrying capacity, and factors that reduce the probability of being caught by radar play an effective role in the self-defense mechanisms of UCAVs (Akyürek, Yılmaz & Taşkıran, 2012). Each technology has unique benefits and limitations in terms of mobility, lethality, flexibility and practicality. Therefore, while today's UAVs are constantly evolving, they can never be invincible. If a UAV is smart enough to avoid physical attacks, its complex sensor and command systems will inevitably increase its vulnerability to electronic counterattacks. When UAVs are confronted with a threat, they must first complete the detection, identification, classification, positioning and tracking process, leaving little time for defense. Therefore, an important problem to be solved is to improve the detection, identification and control capability of UAVs. In this context, new methods and technologies are needed for UAVs (Lyu & Zhan, 2022).

3.2.8. Data links dependency and communication challenges

One of the major limitations of UAVs is their reliance on data links for monitoring and manual control, even though they can perform pre-programmed autonomous missions (Karaağaç, 2016). Data links are affected by factors such as physical distance, signal interference from terrain and weather, limited frequency use, electromagnetic interference, signal strength, and available bandwidth (Gupta & Fernando, 2022; Katrancı, 2020). These dependencies cause losses and interruptions, posing significant obstacles for UAV missions. Additionally, limited transmission range, processing capacity, and slower data speeds are concerns that require further research to advance UAV technology. To ensure efficient, reliable, and safe UAV operations, new regulations and policies must be developed and implemented (Mohsan et al., 2023). Studies indicate that next-generation wireless networks offer great potential for improving UAV data transmission (Khan et al., 2021). Implementing cellular networks for UAVs can increase data rates and help existing networks handle high traffic demands. Efficient UAV deployment can reduce the load on current networks and ensure better quality connectivity.

3.3. What are the Developments that will Affect UAVs? How might UAVs be Shaped in the Future in Light of these Developments?

It is obvious that the dizzying developments in technology will also affect UAV technologies, and that this technology will continue to develop/change rapidly in the near future. This process will increase the critical importance of UAVs for military applications day by day. In this section, technological developments that may affect UAVs and the possible effects of these developments on UAVs are presented in line with the analysis of the documents obtained from the literature review. In this context, the codes obtained as a result of literature review and document analysis regarding the developments that may affect the future of UAVs are given in Table 4.

Table 4. Developments that will affect the effectiveness of UAVs

Codes	References
• Swarm UAV systems	(Carrillo & Borda, 2021; Doğan, 2019; Elmeseiry, Alshaer & Ismail, 2021; Khelifi & Butun, 2022; Mohsan et al., 2023; Zhou, Rao & Wang, 2020; Gargalakos, 2021)
• Wireless power transfer (WPT) technology	(Li, Fei & Zhang, 2019; Chittoor & Bharatiraja, 2022; Elmeseiry, Alshaer & Ismail, 2021; Mahesh, Chokkalingam & Mihet-Popa, 2021; Rong et al., 2023)
• Artificial intelligence, machine learning and deep learning	(Elmeseiry, Alshaer & Ismail, 2021; Helm, et al. 2020; Kurunathan et al., 2024; Mohsan et al. 2022; Puente-Castro et al., 2020; Sands, 2021)
• Blockchain technology	(Alladi et al., 2020; García-Magariño et al., 2019; Javaid, et al. 2021; Mohsan et al., 2022; Schärer & Comuzzi, 2023)
• Advanced sensor and sensing technologies	(Budiyono & Higashino, 2023; Balestrieri et al., 2021; Chandran et al., 2023; Elmeseiry, Alshaer & Ismail, 2021)

3.3.1. Swarm UAV systems

Swarm UAV systems refer to a group of unmanned aerial vehicles operating collaboratively and autonomously to achieve a specific mission. Representing a significant evolution in UAV technology, swarm systems distribute tasks and responsibilities among multiple units, enabling highly coordinated and efficient operations (Khelifi & Butun, 2022). Originally inspired by studies aiming to improve the performance of single-platform UAVs in high-risk missions, swarm UAVs were conceptualized to enhance success rates through collective intelligence (Doğan, 2019). While they were initially developed for military reconnaissance and surveillance, efforts continue to expand their application into other combat-related and civilian domains (Elmeseiry, Alshaer & Ismail, 2021).

Swarm UAVs offer several notable advantages. They operate with minimal human intervention due to their autonomous nature, allowing them to adapt dynamically to changing environments. Their cooperative behavior enables efficient task sharing and parallel processing, increasing mission success. Additionally, their distributed nature provides redundancy and resilience; if one UAV fails, others can compensate, ensuring mission continuity (Kalinbacak, 2023; Zhou, Rao & Wang, 2020). Task delegation among multiple UAVs also alleviates individual load and reduces energy consumption. Integrating energy harvesting systems, such as airframe-mounted solar cells, can further extend their operational duration (Khelifi & Butun, 2022). Despite these advantages, swarm UAVs face several significant technical and operational challenges. Foremost among these are secure and reliable inter-UAV communication and collision avoidance. These challenges become more pronounced as the swarm size increases, leading to higher risks of signal interference and coordination breakdown (Tahir et al., 2019). Standard communication protocols designed for individual UAVs often prove insufficient in swarm scenarios, necessitating the development of new protocols that support secure, scalable, and low-latency communications (Khelifi & Butun, 2022).

Effective communication is particularly critical in military operations, where coordination between swarm UAVs and other ground or aerial units must be seamless and secure (Chen, Yang & Zhang, 2021). Communication can be facilitated via base stations or Wi-Fi based network architectures, but high mobility and dynamic network topologies in UAV swarms demand advanced, adaptive communication strategies. Furthermore, the integration of swarm UAVs into existing 4G and future 5G networks—or ad hoc military networks—could significantly enhance communication range, operational flexibility, and data transmission capabilities (Li, Fei & Zhang, 2019). Such integration would make UAVs more secure, expand their range virtually without limit, and increase their ability to transmit large volumes of data efficiently (Khelifi & Butun, 2022).

Looking forward, swarm UAVs are poised to play a transformative role in military and civilian applications. However, their full potential cannot be realized without overcoming existing technical barriers. Recent advancements in artificial intelligence (AI) and machine learning (ML) present promising avenues for addressing these challenges. AI can support improved path planning, adaptive networking, efficient energy use, and enhanced cybersecurity in UAV swarms (Carrillo & Borda, 2021). Moreover, AI-driven systems may enable swarm UAVs to operate across multiple frequency bands, perform complex joint missions with humans, and react to threats or mission changes in real-time (Gargalakos, 2021). In conclusion, swarm UAV technology holds vast potential for future operations, especially in military contexts. Continued research in AI, communication systems, and control algorithms will be key to overcoming current limitations and unlocking the full capabilities of swarm UAVs.

3.3.2. Wireless power transfer - wireless power transfer (WPT) technology

One of the major barriers to the broader adoption of UAVs in both military and civilian applications is energy consumption and limited battery capacity. Although advancements in battery technologies—such as improved lithium-ion batteries and hydrogen fuel cells—and green energy sources like solar power have extended flight times, studies indicate that the energy harvesting efficiency of these methods remains relatively low (Li, Fei & Zhang, 2019). In this context, Wireless Power Transfer (WPT) technology has emerged as a promising solution for enhancing UAV performance and endurance (Elmeseiry, Alshaer & Ismail, 2021). WPT involves transmitting energy wirelessly from a power source to the UAV without physical connections. This method primarily utilizes electromagnetic fields and may also incorporate radio frequency or laser-based transmission systems (Rong et al., 2023). A ground-based station generates the electromagnetic field, and the UAV's onboard receiver converts this energy into electricity. However, optimizing efficiency and ensuring safe transmission within a specific frequency range remain significant challenges (Mahesh, Chokkalingam & Mihet-Popa, 2021).

Despite its potential, WPT technology is still in development and requires innovations in materials, components, and design to overcome limitations such as transmission losses and electromagnetic interference. Using advanced, lightweight, and compact materials with high-frequency capabilities may improve energy transfer performance (Chittoor & Bharatiraja, 2022). Moreover, integrating WPT systems with emerging technologies such as artificial intelligence, the Internet of Things, cloud computing, and 5G networks could greatly enhance UAV operations. For instance, AI-enabled charging stations could manage power distribution and scheduling for UAV fleets, while 5G connectivity could support real-time communication and data transmission between UAVs and ground control systems (Rong et al., 2023). In conclusion, WPT stands out as a critical area of research that could revolutionize UAV usage by overcoming current energy limitations and enabling more autonomous, longer-duration missions.

3.3.3. Artificial intelligence, machine learning and deep learning

AI, ML and deep learning (DL) have significantly contributed to the advancement of unmanned aerial vehicles (UAVs) and are expected to play an even more transformative role in the future. The concept of AI dates back to the 1950s, initially described as the capability of machines to mimic human intelligence. Over time, with advances in computational power and the availability of large datasets, AI has evolved into a powerful tool applied in various domains such as autonomous vehicles, e-commerce, and personalized services (Helm et al., 2020). AI generally refers to the implementation of algorithms and models that enable machines to perform intelligent tasks, including learning, reasoning, and decision-making (Puente-Castro et al., 2020). ML, a subfield of AI, focuses on designing algorithms that allow systems to learn from data and improve over time. It mirrors the experiential learning of human cognition but enhances it through algorithmic optimization (Kurunathan et al., 2024). DL, a specialized subset of ML, relies on artificial neural networks with multiple layers to process data in a manner similar to how the human brain operates (Helm et al., 2020). These networks are particularly effective in handling complex and high-dimensional data, making DL suitable for image recognition, navigation, and autonomous control tasks in UAV systems.

AI, ML, and DL techniques have enabled significant improvements in UAV applications such as trajectory planning, obstacle avoidance, tracking, battery management, and resource allocation. As UAV onboard computational power increases, it becomes feasible to run sophisticated AI models that allow UAVs to adapt their flight paths, avoid collisions, and make real-time decisions independently (Elmeseiry, Alshaer & Ismail, 2021; Mohsan et al., 2022). For example, ML algorithms are increasingly used in visual navigation, object detection, and behavior prediction. UAVs can utilize onboard cameras and sensors to capture environmental data and use ML techniques to interpret this information, thus enhancing their situational awareness and autonomy (Sands, 2021). Furthermore, deep learning and reinforcement learning techniques have been shown to be effective in solving complex problems such as dynamic obstacle avoidance and real-time trajectory adjustments (Wang et al., 2020). Supervised learning can be used to train UAVs to recognize specific features in an environment, while reinforcement learning allows UAVs to learn from experience to optimize their performance over time. These technologies are particularly useful in applications such as aerial mapping, infrastructure inspection, disaster response, and surveillance, offering improvements in speed, precision, and operational flexibility (Budiyono & Higashino, 2023). Despite these advancements, the implementation of deep learning on UAVs still faces some challenges, particularly due to limitations in energy resources and computational capabilities. Traditional ML approaches are more commonly used due to their lower hardware requirements, but as hardware becomes more efficient, DL is expected to be integrated more extensively into UAV systems (Mohsan et al., 2022). The convergence of AI and UAV technologies continues to create synergies that drive innovation in autonomous aerial systems and expand the range of applications they can support (Kurunathan et al., 2024).

3.3.4. Blockchain technology

Blockchain technology is a decentralized and distributed ledger system that ensures secure, transparent, and immutable recording of transactions over a network. It marks a significant advancement in distributed ledger technology, offering benefits such as enhanced data transparency, error-free transactions, and the elimination of intermediaries (Javaid et al., 2021). In centralized systems, the ledger being controlled by a single entity increases the risk of manipulation or errors. In contrast, a decentralized ledger shared across all participants makes unauthorized alterations extremely difficult, enhancing system reliability (Alladi et al., 2020). In the context of unmanned aerial vehicles (UAVs), blockchain technology offers substantial potential, particularly in addressing security and data integrity challenges. The literature suggests that blockchain can usher in a new generation of secure and adaptive UAV networks. Aerial blockchain systems can prevent communication privacy breaches and ensure the authenticity and accuracy of data collected by UAVs. Additionally, blockchain-based software integrated into UAV networks can support dynamic, flexible, and decentralized communication services capable of real-time decision-making (Mohsan et al., 2022).

Due to their airborne nature, UAVs are prone to risks such as loss, theft, or capture, and face threats to communication, data security, and information management. Blockchain's decentralized nature and use of cryptographic techniques like public key cryptography offer robust solutions to these vulnerabilities. It can protect shared data, verify the accuracy of stored information, and enhance transparency and traceability in UAV operations (Alladi et al., 2020). As UAV usage grows, new challenges emerge, including increased air traffic, optimized route planning, emergency response, swarm coordination, and defense against cyber-physical threats. Blockchain has been proposed as a promising solution to manage these complex tasks securely and reliably. Coordinated UAV systems, especially those involving multiple UAVs or robotic agents, can particularly benefit from blockchain's capabilities, making it easier to synchronize operations while maintaining data integrity and security (Elmeseiry, Alshaer & Ismail, 2021; García-Magariño et al., 2019). Despite its potential, blockchain technology faces several challenges. One major concern is the threat posed by quantum computing. Quantum attacks could exploit the vast processing power of quantum computers to break current cryptographic algorithms, posing a serious risk to blockchain security (Schärer & Comuzzi, 2023). Additionally, blockchain systems are susceptible to majority attacks, which may be enhanced by adversarial machine learning techniques. These vulnerabilities highlight the need for ongoing research to strengthen blockchain networks and ensure their resilience against evolving threats (Alladi et al., 2020; Mohsan et al., 2023).

3.3.5. Advanced sensor and sensing technologies

Advanced sensors and sensing technologies are essential for the successful operation of UAVs. This is because UAVs use sensors in almost every mission or action. For example, collision avoidance, which is an important problem for UAVs, can only be achieved with effective sensors. One of the sensors commonly used in collision avoidance systems is the LIDAR sensor, which can provide 3D maps of the surrounding environment and detect obstacles in real time. In addition, cameras and GPS sensors can be used to provide situational awareness and accurate positioning. Software algorithms such as path planning and collision avoidance systems can be used to analyze sensor data and autonomously steer the UAV around obstacles (Chandran et al., 2023). The development of sensor and sensing technologies enables UAVs to perform a wide range of missions, including surveillance, reconnaissance and search and rescue operations (Budiyono & Higashino, 2023). Some of the main sensor technologies used in UAVs include optical sensors, infrared sensors, radar systems, lidar and sonar. These sensors provide real-time information about the UAV's environment, allowing it to navigate and interact autonomously (Balestrieri et al., 2021). Sensing technologies, such as machine learning algorithms, help interpret sensor data, allowing the UAV to recognize and track objects and make informed decisions. These technologies have advanced significantly in recent years, leading to the development of more complex and capable UAVs with greater levels of autonomy and precision, and these developments are likely to continue in the future.

Current UAV challenges are categorized into technical and operational limitations, such as battery capacity, limited payload, collision avoidance, and cybersecurity vulnerabilities. These challenges are systematically analyzed and linked to emerging technological solutions. For instance, AI-enabled swarm UAVs provide enhanced collision avoidance, dynamic path planning, and coordinated multi-UAV operations, reducing individual workload and increasing mission success. Similarly, advanced payload systems are highlighted for their ability to optimize weight distribution, sensor integration, and operational functionality, allowing UAVs to carry complex mission equipment without compromising performance. Cybersecurity and communication challenges are addressed through secure communication protocols, AI-assisted network management, and blockchain-based frameworks, which offer decentralized, tamper-resistant data management and enhance operational transparency in multi-UAV networks (Wilson et al., 2021). In addition, technologies such as wireless power transfer and solar energy integration are discussed as concrete solutions to improve endurance and operational range.

4. Conclusions

This study analyzes the historical development, current status, and technological challenges of unmanned aerial vehicles (UAVs) in the military domain, while also exploring their potential future roles. Findings indicate that UAVs have effectively undertaken various missions such as surveillance, reconnaissance, strike operations, electronic warfare, and logistics. However, technical limitations such as battery capacity, collision avoidance, cybersecurity, payload restrictions, and communication dependency continue to hinder further advancement.

Emerging technologies, particularly artificial intelligence, machine learning, deep learning, wireless power transmission, advanced sensor systems, and 5G communication, are contributing significantly to overcoming these challenges and enhancing UAV capabilities. These advancements not only improve the performance of individual UAVs but also hold transformative potential for swarm UAV systems, which are poised to become pivotal assets on future battlefields. In conclusion, UAVs are becoming increasingly central to military operations, and as their integration with advanced technologies deepens, they are likely to replace manned aircraft in many missions. Therefore, UAVs are expected to play a key role in shaping future warfare doctrines.

The most important limitation of this study is that it is based solely on a systematic literature review, without experimental or quantitative analysis. Nevertheless, by synthesizing a wide range of academic and policy-oriented sources, this study provides a valuable framework for both researchers and practitioners to understand the past, present, and future of UAV technologies.

A general evaluation of the current state and academic studies on UAVs reveals their increasingly vital role in military applications. With advancing technology, these roles are evolving, and the operational impact of UAVs has significantly grown—and is expected to grow further. It is widely acknowledged that UAVs will become decisive elements on future battlefields, capable of conducting operations independently or in coordination with manned systems. The literature no longer questions whether this will happen, but when. In this context, the transformative potential of UAVs, especially swarm UAVs, necessitates substantial national investment in this sector. As swarm UAVs represent a significant technological leap and are anticipated to be central to future military operations, further in-depth research into their current capabilities and future applications is strongly recommended.

Based on the findings of this study, priority should be given to the development and integration of technologies such as AI-based collision avoidance and swarm UAV coordination into national defense strategies. In addition, experimental studies and advanced research on UAV energy management, data security, and mission optimization should be actively promoted.

Declaration of Competing Interest and Ethics

The authors declare no conflict of interest. This study complies with research publishing ethics. The scientific and legal responsibility for manuscripts published in OPS Journal belongs to the authors.

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