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Turkish Journal of Unmanned Aerial Vehicles

About Journal

The Journal of Turkish Unmanned Aerial Vehicles is a peer-reviewed journal that publishes studies on UAV development, use, and earth sciences and is scanned in International Indexes and Databases. The journal unmanned aerial vehicle (UAV), Unmanned Aerial Vehicle Systems (UAS), and Remote Piloted Aircraft Systems (RPAS), etc. focuses on the design and applications of unmanned aerial vehicles, including. Likewise, contributions based on unmanned water/underwater drones and unmanned ground vehicles are also welcomed.

Aim & Scope

Turkish Journal of Unmanned Aerial Vehicles,

- To inform present to people about the use and developments of UAVs in the fields of Geomatics, Civil, Geology, Environment, Mining, Urban Planning, Agriculture, Archeology and Architecture,
- To provide an easily accessible and wide-ranging discussion environment that will strengthen and accelerate the sharing of knowledge and experience between scientists, researchers, engineers, and other practitioners who are involved in direct or indirect activities with the following topics.
- To contribute to the initiation and development of inter-institutional cooperation, which is of great importance in terms of solving the problems related to professional developments that can play a role in technological and economic development in the world and Turkey

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- ✓ UAV use in military areas (Air-Navy-Army Forces)
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A Bibliometric Analysis on The Use of Unmanned Aerial Vehicles: A Comparative Study of Russia and Türkiye

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Research Article

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Abstract

In recent years, rapid technological developments in information and communication technologies have increased the strategic value of UAVs. In this study, the development processes in terms of UAV technology in Turkey and Russia and their integration into the civil and defense sectors are analyzed comparatively. The two countries have pursued alternative strategies in terms of geographical, industrial, and strategic environments and have invested heavily in UAV technology. This study aims to contribute to scientific studies by determining thematic trends, technological areas, and strategic priorities in terms of UAV studies and applications in both countries. Using bibliometric analysis techniques, annual publications, keyword analysis, and trends in cooperation networks were analyzed in terms of information obtained from the Scopus database between 2005-2025. According to the analysis, Russia focuses on military use of UAV technology and has developed significant improvements in terms of swarm control systems, energy efficiency, and secure communication. Turkey, on the other hand, supports domestic production in the defense sector as well as in civilian applications such as agriculture, disaster management, and infrastructure monitoring, and focuses on 5G integration with artificial intelligence-based optimizations. In this study, individual approaches of Türkiye and Russia in terms of UAV technology and their value in terms of international defense and sustainable development were emphasized and it was determined that UAV technology has a widespread potential in terms of both scientific and applicable studies.

Keywords: Unmanned aerial vehicles, drones, bibliometric analysis, Turkiye, Russia.

İnsansız Hava Araçlarının Kullanımına İlişkin Bibliyometrik Analiz: Rusya ve Türkiye'nin Karşılaştırmalı Araştırması

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Özet

Son yıllarda bilgi ve iletişim teknolojilerindeki hızlı teknolojik gelişmeler, İHA'ların stratejik değerini artırmıştır. Bu çalışmada, Türkiye ve Rusya'da İHA teknolojisi açısından gelişim süreçleri ve bunların sivil ve savunma sektörlerine entegrasyonu karşılaştırmalı olarak analiz edilmiştir. İki ülke coğrafi, endüstriyel ve stratejik ortamlar açısından alternatif stratejiler izlemiş ve İHA teknolojisine büyük yatırımlar yapmıştır. Bu çalışma, her iki ülkede İHA çalışmaları ve uygulamaları açısından tematik eğilimleri, teknolojik alanları ve stratejik öncelikleri belirleyerek bilimsel çalışmalara katkıda bulunmayı amaçlamaktadır. Bibliyometrik analiz tekniği kullanılarak, 2005-2025 yılları arasında Scopus veri tabanından elde edilen bilgiler açısından yıllık yayınlar, anahtar kelime analizi ve işbirliği ağlarındaki eğilimler analiz edilmiştir. Analize göre, Rusya'nın İHA teknolojisinin askeri kullanımına odaklandığı ve sürü kontrol sistemleri, enerji verimliliği ve güvenli iletişim açısından önemli iyileştirmeler geliştirdiği görülmektedir. Türkiye ise savunma sektörünün yanı sıra tarım, afet yönetimi ve altyapı izleme gibi sivil uygulamalarda yerli üretimi desteklemekte ve yapay zeka tabanlı optimizasyonlarla 5G entegrasyonuna odaklanmaktadır. Bu çalışmada, Türkiye ve Rusya'nın İHA teknolojisine ilişkin bireysel yaklaşımları ve uluslararası savunma ve sürdürülebilir kalkınma açısından değeri vurgulanmış olup, İHA teknolojisinin hem bilimsel hem de uygulanabilir çalışmalar açısından yaygın bir potansiyele sahip olduğu belirlenmiştir.

Anahtar Kelimeler: İnsansız hava araçları, dronlar, bibliyometrik analiz, Türkiye, Rusya.

1. Introduction

Rapid advances in information and communications technology over the past decade have immensely boosted the strategic value of unmanned aerial vehicles (UAVs). With no pilot and with provisions for autonomous and remotely operated use (Eisenbeiss, 2004; Kiss et al., 2024), these aerial platforms have changed civilian and defense use with ease, efficiency, and cost-effectiveness (Ayamga et al., 2021). Today, UAVs have numerous civilian uses such as agricultural use, infrastructure observation, and disaster management, and even in real-time intelligence, observation, scouting, and target accuracy in operations in the military (Abdelmaboud, 2021; De Rango et al., 2017; Elmokadem & Savkin, 2021; Telli et al., 2023). As seen in the ongoing conflict between Russia and Ukraine, the use of UAVs on modern battlefields has transformed operational capabilities for armies and significantly enhanced their value in the defense sector (Erceg et al., 2017). Despite that, UAVs have not been restricted to defense but have played an important role in scientific and industrial sectors (Sivakumar & TYJ, 2021). That confirms multi-purpose use potential for technology in UAVs and its value at a worldwide level.

Many countries in the world have significant investments in UAV technology in an attempt to make both civilian and defense problem-solving a reality. In such a scenario, Turkiye and Russia have emerged two significant players with contrasting geopolitical standings and industrial settings. With a specific consideration for its use in the military, Russia has developed cutting-edge technology in terms of decentralized swarm management, ultra-reliable low-latency communications, and blockchain in an attempt to enhance operational capabilities, particularly in hostile environments (Izhboldina & Lebedev, 2023; Kapitonov et al., 2017). Russia's effectiveness in utilizing its application of its use of military UAVs is backed through a robust technology base in intelligence, observation, and accuracy in targeting. On the other hand, state-of-the-art technology in efficiency in terms of information and energy distribution possesses effective alternatives for new forms of warfare (Abdelmaboud, 2021; Telli et al., 2023).

Similarly, Turkiye, in recent years, has developed immensely in technology in terms of UAVs. Turkey's transition in this direction has been driven by the motive of reducing dependence on external sources in the defense sector and achieving self-sufficiency. Besides, civilian use of UAVs, too, have been discovered. With software and artificial intelligence-based network technology, Turkiye optimized performance in 5G communications, disaster management, agricultural use, and infrastructure observation (Abdulsalam et al., 2023; Yazici et al., 2023). Turkiye, which is situated in a high-risk zone for natural disasters, is a forerunner in developing new approaches for utilizing such technology in civilian operations and in disaster management. In such a scenario, use of UAVs comes out to be a multi-purpose tool in both civilian and defense sectors (Tahir et al., 2023).

This study highlights Russia and Turkiye's innovations in UAV technologies from a comparative perspective in the context of their operational applications and strategic priorities. By reviewing the existing literature in detail and analyzing current trends, the strengths and weaknesses of these two countries in UAV technologies and their future perspectives are evaluated. Also, the impact of UAVs, which plays a pivotal role in the defense industry, on civilian sectors are emphasized and the diverse dimensions of these technologies are discussed. Although there are studies that separately address the developments in the UAV field of Russia and Turkiye, comparative studies focusing on the integration of these two countries into defense as well as civilian applications are limited. This study aims to fill this gap in current literature by comprehensively examining the dual-use potential and strategic outcomes and effects of these technologies.

2. Background

UAVs have become cutting-edge systems with widespread use in technology and defense in a relatively short period of time. They function with no operators, working in an autonomous manner, and remotely, and their key strengths include minimizing danger to humans, continuity in operations, efficiency in terms of weight, and economy (Miller & Chadwick, 2018). These benefits have firmly positioned UAVs as important assets, specifically in regards to use in the military, for use in spying, observation, and real-time intelligence collection in an effort to target enemy locations and assess scenarios.

Advanced UAVs with guided ammunition have entered most nations' arsenal with capabilities for delivering pinpointed attack with minimum loss (Hemmati et al., 2023; Kotsemir, 2019). For instance, in the case of the Russia-Ukraine war, UAVs revolutionized military operations with new dimensions in observation and intervention processes(Horowitz and Fuhrmann 2014). Historically, UAV technology traces back to rudimentary examples like the explosive-laden balloons used in Venice in 1849 (Daly, 2025). Significant advancements followed during the World Wars, where UAVs were employed for reconnaissance and training (Gonzalez-Aguilera & Rodriguez-Gonzalvez, 2017). Today, UAVs serve diverse functions ranging from air strikes to missile defense and border security.

Beyond military applications, UAVs have transformative potential in both scientific research and civilian use. With its adaptability and versatility, its use in infrastructure planning, agricultural use, and disaster management make it a transformation in such sectors. With 5G networks and software-defined networks, UAVs make operations efficient in commercial and logistic operations worldwide. For example, 5G-integrated networks for UAVs allow for increased communication between drones and optimized path planning, enhancing its use in commercial and defense-related logistically (Solomitckii et al., 2018; Ullah et al., 2020).

This global development situates Turkiye and Russia, both of whom have been actively investing in technology for UAVs, in a certain position. Turkiye and Russia have a complex and ever-evolving past, with a history of both confrontations and cooperation, including wars, territorial disputes, and shifting alliances. However, in the post-Cold War era, economic cooperation and regional security have become defining features of their interactions (Balta & Özel, 2021). Economic collaboration accelerated in the early 2000s, particularly with energy projects like the Blue Stream and TurkStream pipelines, which positioned Russia as a key supplier of natural gas to Turkiye (Sapmaz, 2023). Additionally, the Akkuyu Nuclear Power Plant symbolizes strategic partnerships between the two nations (Kıllıoğlu, 2023)

Despite these events, political contradictions can nevertheless be seen. There have been conflicting interests heightened through the Syrian civil war, with Turkiye supporting anti-regime groups and with Russia supporting the regime, with direct confrontations in areas of dispute (Köstem, 2021). Similarly, differences in Libya—where Russia backed General Haftar and Turkiye supported the Tripoli-based government—exemplify ongoing tensions in their foreign policy agendas (Bayhan et al., 2021).

In terms of UAV improvements, Russia’s research focuses mostly on military applications, emphasizing swarm dynamics, decentralized control, and energy efficient path planning (Izhboldina & Lebedev, 2023). Technological developments like more steady low-latency communication (uRLLC) and blockchain integration enhance Russia’s UAV operations, ensuring secure and more reliable data sharing in challenging environments (Kapitonov et al., 2017). Moreover, detection technology with artificial intelligence and remote sensing secure airspace, and range and source improvement through microwave radiation work towards extending range for UAV (Zhukov et al., 2017).

UAV development reflects both domestic and global aspirations — with a focus on integrating artificial intelligence and optimization techniques into UAV systems for 5G and beyond in Turkiye (Yazici et al., 2023). Turkiye’s improvements in its native platforms such as Bayraktar TB2 and ANKA have proven successful in countries such as: Syria, Libya, and Nagorno-Karabakh. Military, civilian, and commercial requirements have been addressed through these technologies, with use in precision agriculture, infrastructure observation, and disaster management (Abdulsalam et al., 2023). Also, Turkiye’s geographical structure and agricultural potential position UAVs as essential for improving productivity in tasks such as crop monitoring and yield estimation (Uysal et al., 2015)

As a result, Turkiye and Russia's investments in technology for UAVs says a lot about its worth in modern warfare and overall usage. Energy efficiency, real-time processing, and technological versatility are areas that must see ongoing innovation. All these breakthroughs highlight a lot about each country's personal concerns and present an illustration of the role of UAVs in redefining modern trends in international security areas.

3. Methodology

Bibliometric analysis is a general tool used to examine the scientific environment in a specific field in terms of publications, keywords, collaborations, and trends over the years. These analyses cover both quantitative and qualitative data, allowing for a comprehensive assessment of the scientific output of the field. Thanks to bibliometric analysis methods, important elements such as fundamental studies, most cited articles, influential authors, and leading research institutions in the relevant field can be determined. These analyses, which reveal research trends by examining the distribution of publications over the years, visualize the frequency and common use of keywords with network structures, and clarify the relationship between the topics. It also determines the basic themes and their subcategories through conceptual maps and presents the collaboration structure between authors and institutions in the form of collaboration networks. Within the scope of this study, the trends in the technological and strategic approaches of Turkey and Russia in the field of unmanned aerial vehicles (UAVs) were comprehensively examined using these analysis methods. Both countries make significant contributions in terms of UAV technologies and strategic applications on a global scale. Therefore, the bibliometric methods and visual tools used play a critical role in presenting the historical development, current status, and potential future directions of the relevant field systematically and understandably.

Data preprocessing constitutes an important basis for any bibliometric analysis and text mining. First, variation in keyword forms, synonyms, and abbreviations have been addressed in this study in an effort to make the dataset uniformed. Names of authors have also been checked in an effort to map intellectually accurately. In this study, similar keywords have been merged, singular and plural forms have been normalized, and no variation in name of authors have been encountered. All these processes count in providing strong results and in curving any kind of noise in bibliometric studies (Zupic & Čater, 2015).

This study utilized a tool, namely, Bibliometrix (Aria & Cuccurullo, 2017), a proven tool for use in bibliometric analysis, and its friendly companion tool, Biblioshiny. We chose to use Bibliometrix for its ease in providing in-depth analysis of bibliometric information. Those features include keyword mapping, collaboration networks, and theme development. We chose to use the Scopus database for its multidisciplinary and aptitude for use in required bibliometric analysis (Mongeon & Paul-Hus, 2016). By using these tools, we were able to perform in depth analyses of publication trends, keyword frequencies, and collaborative networks.

The flowchart (Figure 1) highlights the methodological steps which are undertaken in this study. That capsulates the process starting from initial data extraction to advanced bibliometric analyses. The flowchart highlights the number of documents retrieved and the systematic process used to conduct this research. These processes included formulating correct search queries, well-refining the dataset through given filters, and performing manual screenings to ensure steady relevance level.

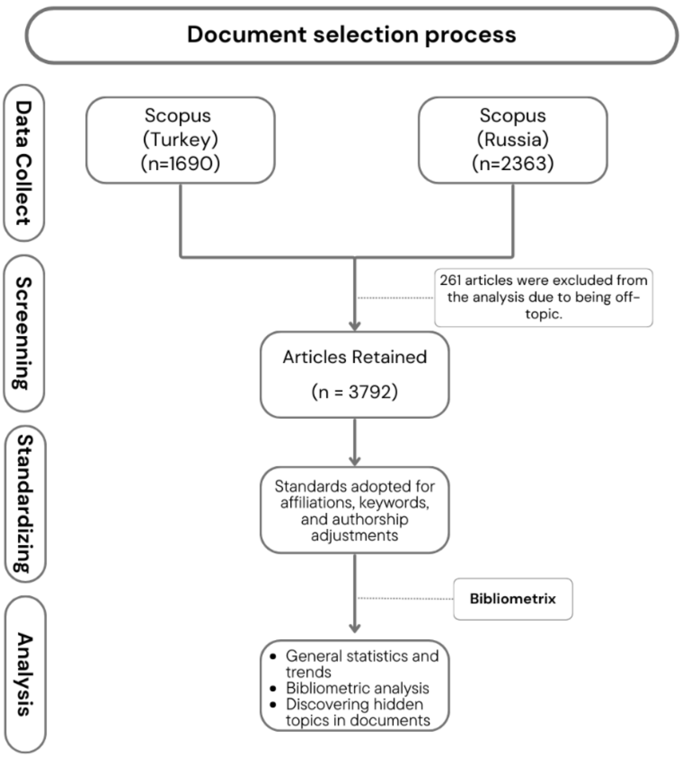


Figure 1. Flowchart of the Methodological Steps in Bibliometric Analysis.

3.1. Bibliographic Base

In order to find research trends, technology advancement, and strategic agenda regarding unmanned aerial vehicles (UAVs) in Turkiye and Russia, we searched publication histories between 2005 and 2025. Scopus was selected as the primary bibliographic database because of its wide diverse coverage and valuable indexing capabilities. Scopus is known well as a trustworthy tool for bibliometric studies, and it provides consistent and comprehensive access to literature (Elsevier, 2020).

3.2. Bibliographic Base Search Strategy and Screening Records

Queries were carefully constructed to capture publications explicitly associated with UAVs while ensuring precision and relevance. The search queries targeted publications in English to maintain consistency and focused on scientific contributions explicitly related to Russia and Turkiye. The detailed queries (Table 1) were structured as follows.

The inclusion of a specific timeframe (2005–2025) ensured that the analysis captured two decades of research activity, reflecting long term trends and recent improvements. The focus on English-language publications enhanced comparability and reduced linguistic inconsistencies.

After retrieving the datasets, the records underwent multiple refinement steps:

1. ***Filtering***: Initial filtering excluded non research articles, that is, editorials, book chapters, and conference abstracts, to include only peer reviewed scientific contributions.
2. ***Manual screening***: Titles and abstracts were screened to verify the relevance of every publication. Entries that were not related to UAVs or not directly connected with either Russian or Turkish research were excluded.
3. *Data Cleaning:* Standardized terminology was applied to keywords, and author affiliations were checked for potential inconsistencies to improve accuracy.

The datasets extracted from Scopus were processed using the package Bibliometrix and its tool Biblioshiny. These tools enabled the generation of visualizations such as:

1. *Annual Scientific Production:* Identifying trends in publication volume over the specified timeframe.
2. *Keyword Co-occurrence Networks:* Mapping the relationships between frequently used terms.
3. *Collaboration Networks:* Depicting institutional and international research partnerships.
4. *Thematic Evolution:* Highlighting emerging research topics and their progression.
5. *Conceptual Structure Maps:* Visualizing clusters of research focus areas.

The results were further refined by manually screening retrieved records to exclude irrelevant entries. The inclusion of only English-language publications may exclude regionally significant research published in other languages. Additionally, the study focuses solely on UAV research explicitly attributed to Russia and Turkiye, potentially overlooking collaborative works that are not directly affiliated with these countries.

To account for the differing research dynamics in Russia and Turkiye, the analysis is structured into two distinct sections. Each country's contributions are assessed individually, followed by a comparative evaluation of developments, trends, and potential. This approach ensures a nuanced understanding of UAV research trends in both nations.

Table 1. Detailed research query

Country	Query	Description
Russia	*TITLE-ABS-KEY ("UAV" OR "unmanned aerial vehicle" OR "military drone" OR "defense drone" OR "combat drone") AND PUBYEAR > 2004 AND PUBYEAR < 2026 AND (LIMIT-TO (AFFILCOUNTRY , "Russian Federation")) AND (LIMIT-TO (LANGUAGE , "English"))*	This query specifically searched for publications containing terms such as "UAV," "unmanned aerial vehicle," "military drone," "defense drone," or "combat drone" in the title, abstract, or keywords. It restricted the results to articles affiliated with the Russian Federation and published in English between 2005 and 2025.
Türkiye	*TITLE-ABS-KEY ("UAV" OR "unmanned aerial vehicle" OR "military drone" OR "defense drone" OR "combat drone") AND PUBYEAR > 2004 AND PUBYEAR < 2026 AND (LIMIT-TO (AFFILCOUNTRY , "Turkey")) AND (LIMIT-TO (LANGUAGE , "English"))*	Similarly, this query was designed to retrieve publications associated with UAV research in Turkiye, applying the same terms and timeframe as the Russian query while limiting the results to Turkish affiliations

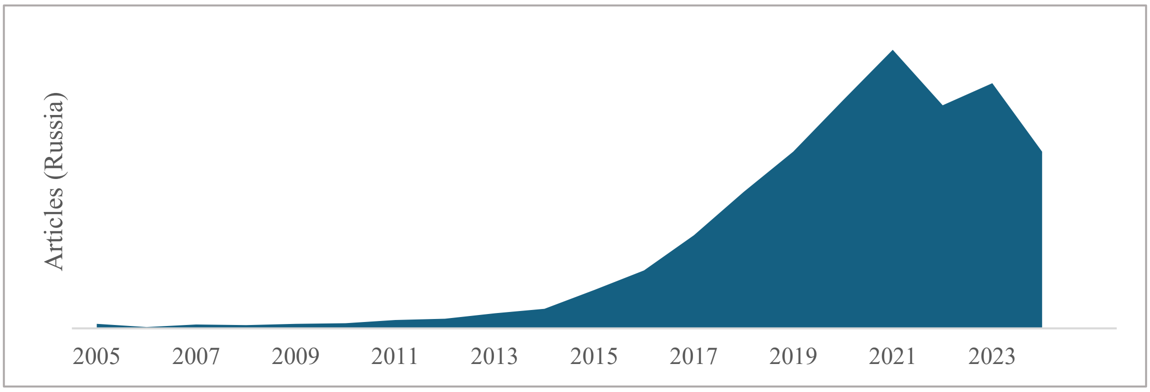
4. Analysis and Results

Given that Turkey and Russia exhibit different technological and strategic dynamics, their UAV-related data and analyses are addressed separately. This section presents the developments in UAV technologies for each country, accompanied by relevant bibliometric findings and thematic insights.

Figure 2 (a) shows from 2005 to around 2010 that the number of published scientific articles remained relatively low and stable. There was little change in the number of publications during this period. This phase likely reflects the nascent stage of UAV research and development in Russia, where foundational technologies and initial exploratory studies were being established.

Starting around 2011, there is a significant and steady increase in the number of articles published annually. This trend peaks around 2020 or 2021, showing the highest annual production. This steep curve indicates heightened interest, with Russia focusing on UAV applications in military, agriculture, and environmental sectors. Increased research activity is linked to developments in artificial intelligence, hyperspectral imaging and IoT applications in UAV systems, such as studies Lu et al. (2023) and Podlesnykh et al. (2024).

a) Russia



b) Turkiye

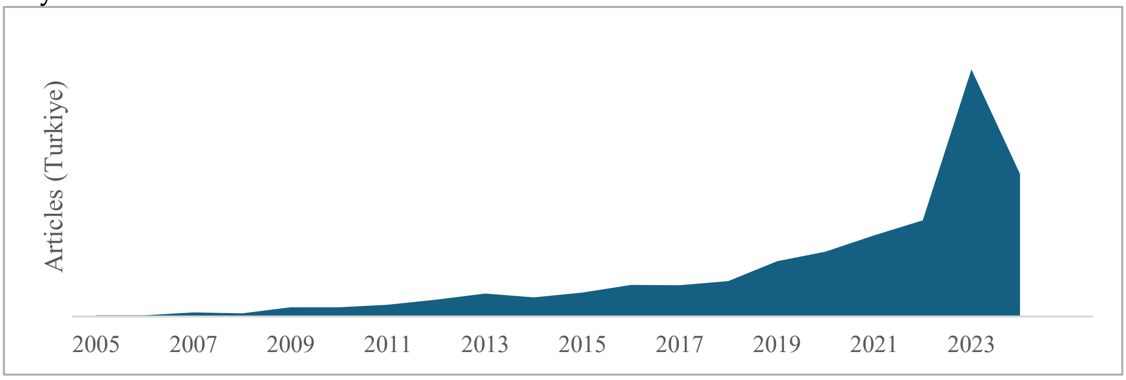


Figure 2. Annual Publication Trends in UAV Research for Russia and Turkey (2005-2025).

Scientific production in UAV research peaked in 2021, followed by a gradual decline in 2022 and 2023, likely due to topic saturation and emerging new research fields such as 5G communications. Causes for the decline are possible due to saturation in research topics, other more global constraints such as COVID-19, and possibly new priority interests in communications research with the latest systems like 5G and NOMA VLC systems. This shift indicates a transition from basic exploratory research to more application-oriented UAV studies. This trend indicates a change in focus from basic to applied research on UAVs.

Figure 2 (b) shows a significant increase in Turkiye's studies on UAV and drone technologies after 2015. The increase observed in UAV and drone technologies in Turkiye after 2015 can be associated with multiple internal and external dynamics. Following 2016, Turkey intensified efforts to reduce external defense dependency, leading to increased investments in both military and civilian UAV applications.

The increase after 2020 can be explained by the innovative needs brought about by the pandemic Mohsan et al. (2022) and the acceleration of the integration of advanced technologies such as artificial intelligence with UAVs. Increasing security threats and cross-border operations in Turkiye have increased the importance of military UAVs. Strategic investments in defense and R&D initiatives aimed at both military and civilian UAV applications significantly accelerated scientific output in the field. The graph confirms that UAV technology is rapidly developing, multidisciplinary, and application-oriented field in the literature, while also highlighting the strategic importance of growth in this field.

"Antennas" is the most frequently occurring keyword with 1,188 occurrences (Figure 3 (a)). This indicates its centrality in UAV research, particularly in enhancing communication, navigation, and sensing capabilities. Remote Sensing" appears second with 346 occurrences, pivotal in environmental monitoring, military operations, and navigation. Similar to Gyrichidi et al. (2024) work, "Air Navigation" (251 occurrences) emphasizes the importance of aviation technologies. "Aircraft Control" (245 occurrences) and together with "Aircraft Detection" (206 occurrences) emphasize automation, safety, and defense systems Keywords like "Robotics" (205 occurrences), "Computer Vision" (164 occurrences), and "Deep Learning" (156 occurrences) demonstrate the integration of AI in UAV applications.

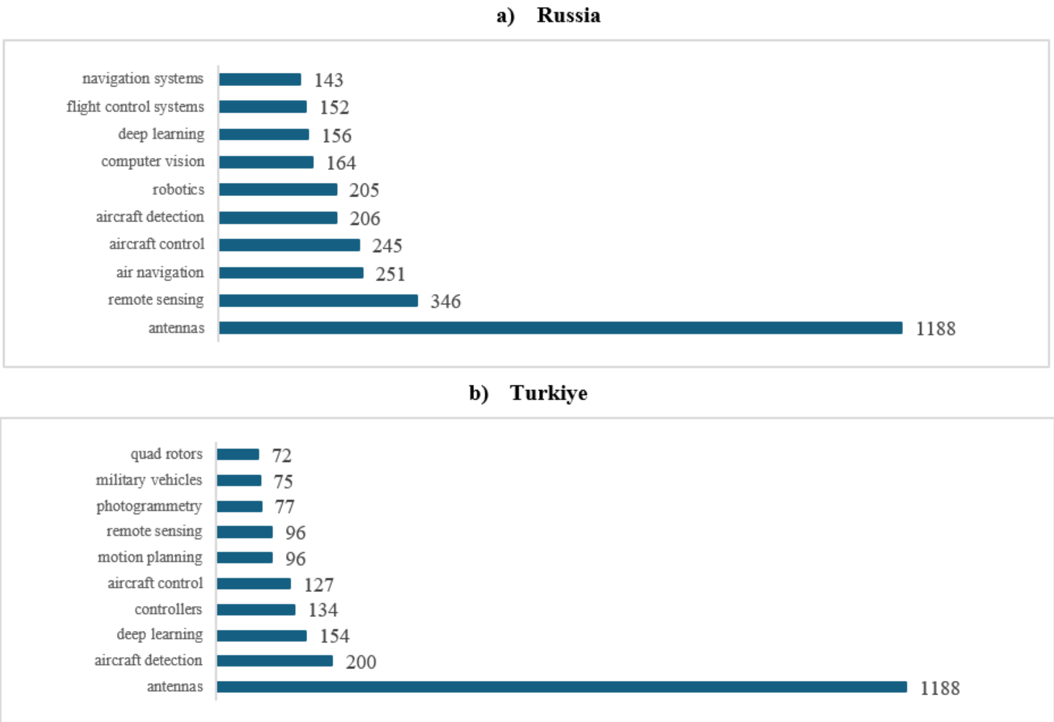


Figure 3. Frequency Distribution of Keywords in UAV Studies for Russia and Turkey.

The prolific diversity of keywords, from AI-related topics to domain-specific terms, highlights a multidisciplinary approach. IoT and optimization technologies highlight the integration of connected systems and computational advancements in traditional UAV fields. Similar to the studies by Gyrichidi et al. (2024), Uzhinskiy (2023), and Zvezdina et al. (2024), keywords such as "Agricultural Robots," "Aerial Photography," and "Forestry" show practical applications in environmental, industrial, and aviation contexts. The prevalence of terms such as "Deep Learning," "Computer Vision," and "Convolutional Neural Networks" reflects the increasing adoption of AI-driven methodologies, as in the studies by Podlesnykh et al. (2024) and Uzhinskiy (2023).

Figure 3 (b) shows that Turkiye's research focuses on UAV and drone technologies, especially in areas such as "antennas" and "aircraft detection". This supports the strategic importance of UAVs in communication systems and security applications emphasized by Al-Turjman et al. (2020) and Yazici et al. (2023). This intense emphasis on antenna technologies is in line with Turkiye's goals of reducing external dependency on border security and the defense industry. Keywords such as "deep learning" and "motion planning" reveal the critical role of artificial intelligence and route planning technologies to improve the autonomous functions of UAVs. In addition, the interest observed in areas such as "photogrammetry" and "remote sensing" supports Turkiye's efforts to disseminate UAV technologies in civilian applications such as agriculture, environmental monitoring, and disaster management.

Smaller terms like "multi-agent systems" and "control systems" suggest areas where research is still growing but holds potential for future breakthroughs (Figure 4(a)). Deep Learning, Optimizations, and Learning Systems show increased relevance, marking a shift towards AI and optimization techniques. Keywords like "Kalman Filters," "Control Systems," and "Navigation" show spikes, likely due to breakthroughs or project-focused research.

The weight of terms such as "antennas" and "aircraft detection" in the word cloud in Figure 4 (b) shows that Turkiye focuses on communication infrastructure and detection systems in UAV technologies. While Ullah, Al-Turjman, & Mostarda (2020) and Yazici et al. (2023) emphasize the critical role of these technologies in in- creasing the operational effectiveness of UAVs, Zaid et al. (2024) state that artificial intelligence-based detection systems provide strategic advantage, especially in military operations. In addition, the prominence of concepts such as "deep learning" and "motion planning" reflects the increasing work on algorithms that support the autonomous functions of UAVs. In addition, the keywords "photogrammetry" and "remote sensing" indicate that the use of UAVs in agricultural and environmental monitoring applications is becoming widespread, in line with studies such as Uysal et al. (2015) and Aslan et al. (2022). According to these data, it has been observed that Turkiye gives strategic priority to communication and artificial intelligence-based innovations in UAV research focusing on both defense and civilian applications.

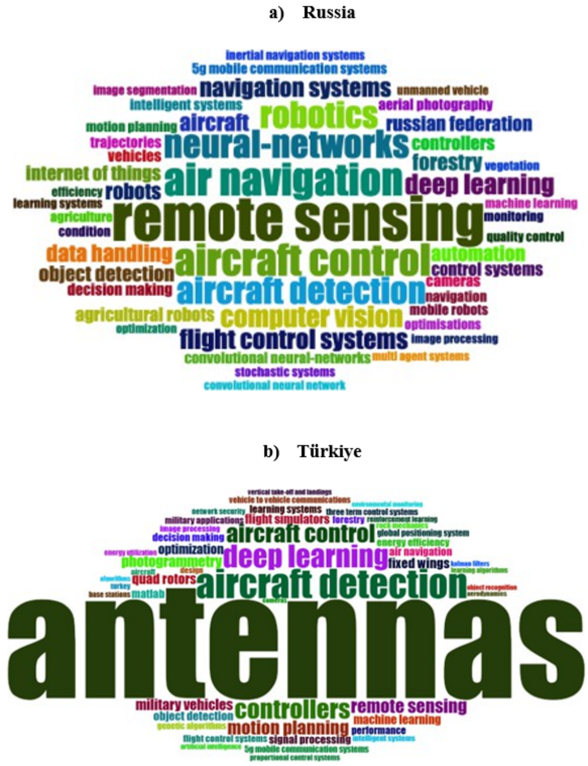


Figure 4. Keyword Cloud Representation Highlighting Research Focus Areas.

Figure 5. Keyword Occurrence Trends in UAV Research.

Foundational bold topics like "Algorithms" and "Vehicles" appeared early in UAV research. These subjects laid the groundwork for advancements in UAV systems, emphasizing the development of essential technologies like navigation, control, and sensing mechanisms. The early focus on these foundational topics helped establish critical pathways for integrating advanced technologies later, such as AI and IoT (Figure 5 (a)). Over time, these foundational studies were instrumental in transitioning the field towards more application-driven innovations in agriculture, defense, and environmental monitoring.

Figure 5 (b) clearly shows the focal points of research in the field of UAVs and is consistent with current trends in literature. For example, the fact that antenna technologies occupy the largest area in the graph with 22% supports the fact that communication infrastructure is a critical component for UAVs, as emphasized in studies such as Ullah, Al-Turjman, & Mostarda (2020) and Yazici et al. (2023). Similarly, the prominent presence of deep learning (4%) and machine learning (3%) categories reflects the increasing interest in using UAVs in artificial intelligence-based applications such as object detection, route optimization, and autonomous movement. The lower representation of environmental applications such as photogrammetry (2%) and forest monitoring (2%) show that the use of UAVs in precision agriculture and environmental protection areas is still in the development stage in Turkiye. While this situation arises as a result of Turkiye's concentration on UAVs in the defense industry Altan & Hacıoğlu (2020), it also points to the need to focus more on civil and environmental applications.

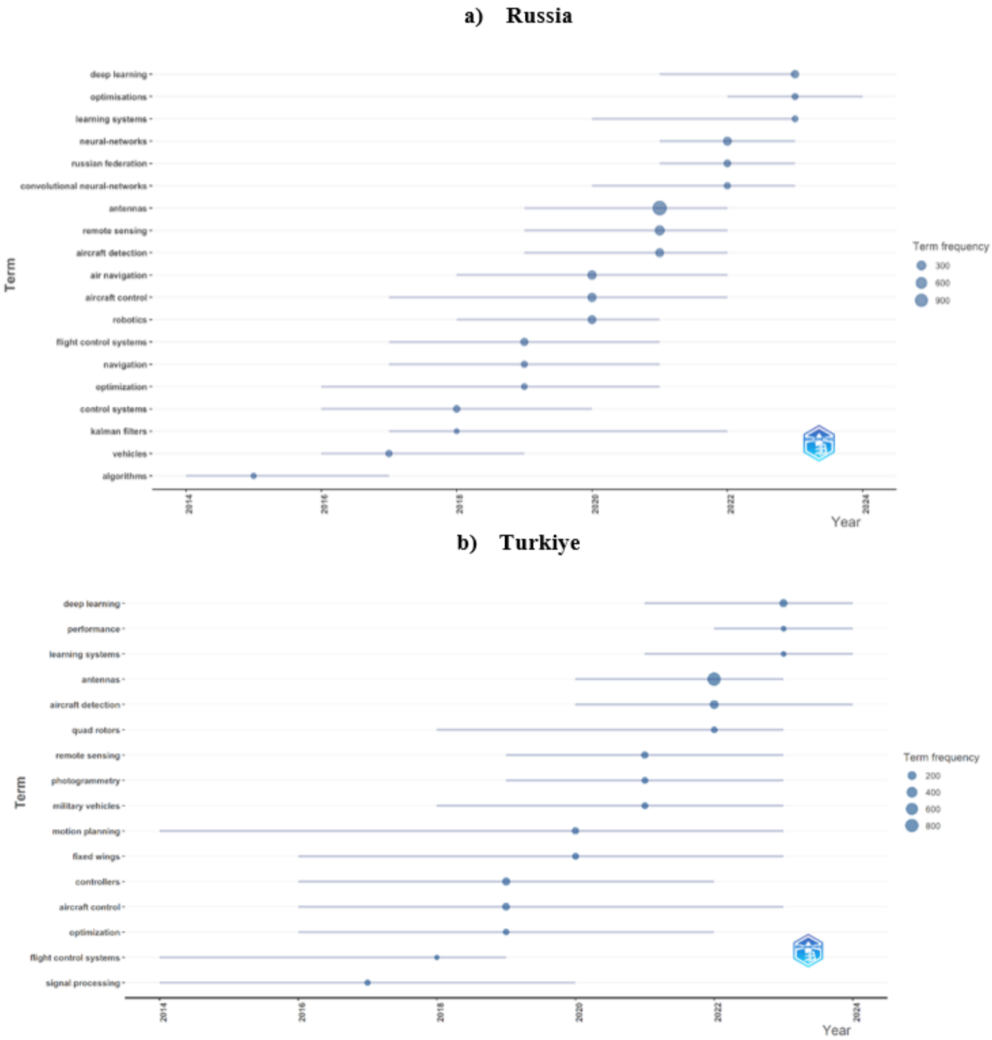


Figure 6. Thematic Trend Evolution in UAV-Related Studies.

The corelated relation between foundational engineering topics and applied AI technologies demonstrates a multidisciplinary approach to UAV research (Figure 6 (a)). Keywords like "Navigation Systems," "Aircraft Detection," and "Control Systems" exemplify the bridging of traditional engineering concepts with cutting-edge AI applications. This integration underscores the importance of interdisciplinary collaboration in advancing UAV capabilities across diverse domains.

Figure 6 (b) shows how exactly the main trends in UAV technologies have improved over the years. In particular, the frequency of the terms "antennas" and "aircraft detection" reflects Turkiye's heavy investments to make its UAVs more effective in the defense industry. Also, the rise of AI focused concepts such as "deep learning" and "motion planning" reveals a global trend toward developing the autonomous capabilities of UAVs, consistent with studies such as Abdulsalam et al. (2023) and Zaid et al. (2024).

The more prominent use of the term's "photogrammetry" and "remote sensing", especially after 2015, shows that Turkiye has begun to benefit from these technologies in areas such as agriculture and environmental monitoring. On the other word, the frequency of concepts such as “military vehicles” and “controllers” confirms the critical importance of UAVs in military and border security applications emphasized by Altan & Hacıoğlu (2020) and Sözen & Craparo (2016).

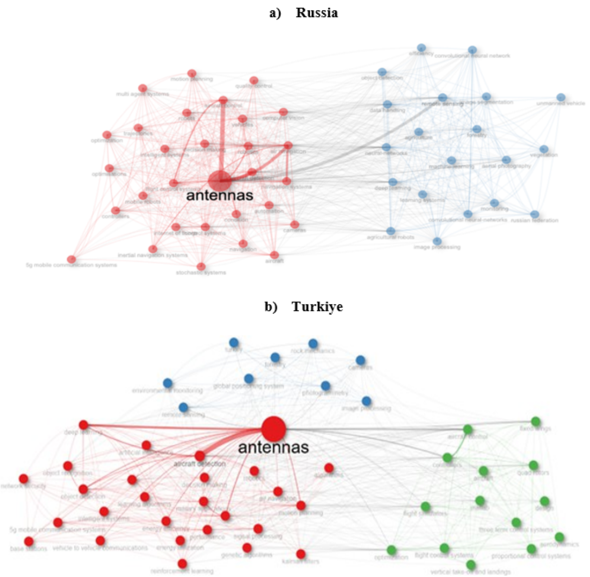


Figure 7. Conceptual Relationships and Clusters in UAV Research Keywords.

“Antennas,” “Remote Sensing,” and “Aircraft Detection” dominate research, indicating their importance in communication, sensing, and aviation (Figure 7 (a)). Topics like “Air Navigation” and “Robotics” hold foundational relevance but need further exploration (Figure 8 (a))

Figure 7 (b) shows the conceptual correlations and focal points in those studies exported. In this graph, the most important node is “antennas”, reflecting the vital role of UAVs in the communication infrastructure. More concretely, in another paper authors underline the fact that antenna technologies are too critical to UAVs’ data transfer performance over large networks (Ullah, Al-Turjman, & Mostarda (2020). The importance of the concepts related to “aircraft detection” is strengthened through the use of artificial intelligence and deep learning algorithms for object detection and security applications by Zaid et al. (2024) and Shayea et al. (2022). It is a strategic reflection of investments in UAVs by Turkiye for border security and military applications.

Green nodes such as “optimization” and “motion planning” represent solutions to increase the operational effectiveness of UAVs. The control algorithms which are developed by (Altan & Hacıoğlu, 2020) and the route planning approaches which are proposed by (Pehlivanoglu (2012) support innovative efforts in these prominent areas. Also, blue nodes such as “remote sensing” and “photogrammetry” shows how photogrammetry techniques discussed by Uysal et al. (2015) and Yaprak et al. (2018) provide an effective solution in environmental monitoring and precision agriculture applications. This indicates the potential of Turkiye to use UAVs in civil applications as well.

The wide network of connections in the graph reflects the different nature of UAV research. For example, the physical layer security techniques have been discussed by Hamamreh et al. (2019) are mostly linked to “signal processing” and are of utmost importance for ensuring data security in UAV communication. Also in the same manner, Malekloo et al. (2022) emphasized the use of UAVs in structural health monitoring systems by the evaluation of the non-interruptible connection of machine learning algorithms with the newly introduced “deep learning” node.

Also keywords like “antennas”, “motion planning” and “military vehicles” in the “Basic Themes” section in Figure 8 (b) emphasize Turkiye’s strategic priorities in improved UAV technologies. Al-Turjman et al. (2020) and Yazici et al. (2023) drew huge attention to the most important role of antenna technologies in the communication infrastructure and stated that this area is a fundamental research focus for UAVs. At the same time, some studies on “motion planning”, aligned with studies such as Pehlivanoglu (2012) and Altan & Hacıoğlu (2020) shows the importance of auto-path optimization and stability in the realization of autonomous missions. The theme of “military vehicles” reflects Turkiye’s strong investments in the defense industry and its technological independence goals in this area.

“Niche Themes”, “aircraft detection”, “deep learning” and “remote sensing” focus on advanced technologies Abdulsalam et al. (2023) and Ullah, Al-Turjman, & Mostarda (2020) have demonstrated how deep learning algorithms improve the autonomous functions of UAVs in applications such as object detection and environmental monitoring. This situation overlaps with Turkiye’s efforts to increase its potential in civil applications such as agriculture and environmental management. Among the developing or declining themes, “controllers”, “aircraft control” and “quad rotors” may indicate that previous studies on the development of basic systems are maturing. Altan & Hacıoğlu (2020) emphasized the im- portance of control algorithms in the stabilization and precision of UAVs and stated that these technologies have a critical role in defense and commercial applications.

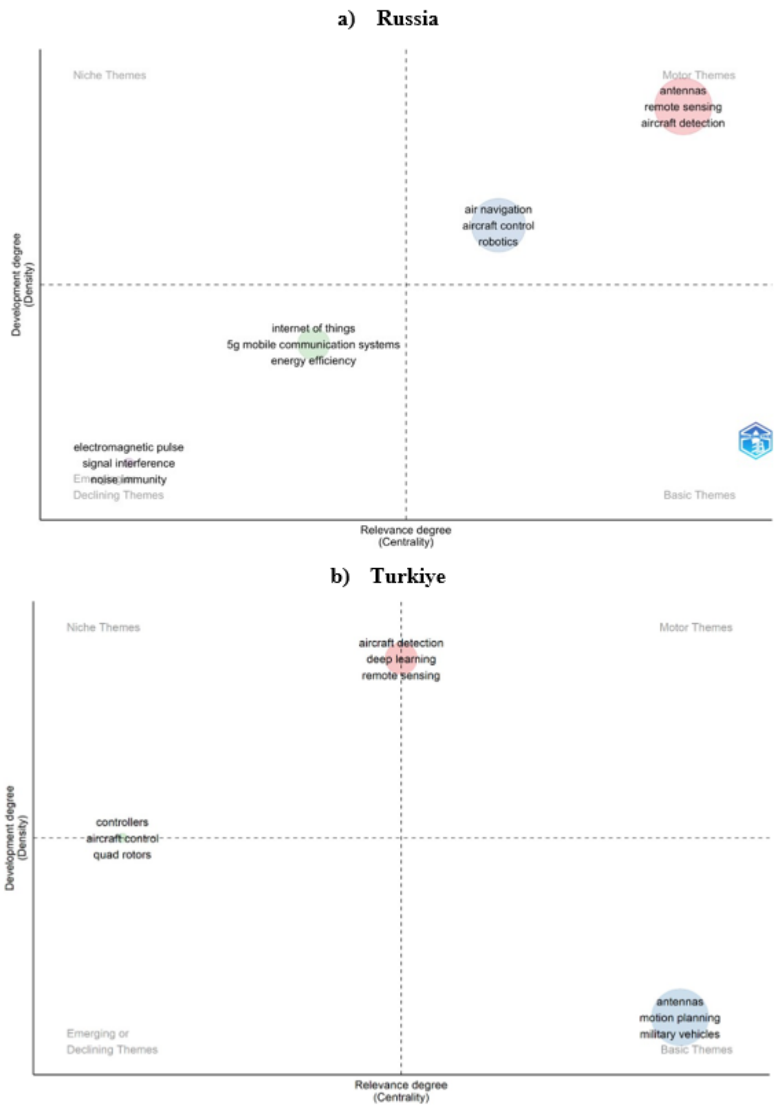


Figure 8. Centrality Analysis of Keywords in UAV Research Themes.

In Figure 9 (a), the Blue Cluster focuses on keywords such as Aircraft, Deep Learning, and Remote Sensing, and highlights AI-powered decision-making processes in aviation. The Pink Cluster focuses on computational techniques, drawing attention to optimization and intelligent systems. The Red Cluster addresses forestry, aerial photography, and remote sensing, and reflects environmental monitoring applications. The Green Cluster includes IoT and 5G mobile communication systems, which symbolize the advances in connectivity technologies, in line with the Ma et al. (2023) study. According to Dimensional Importance, it represents a wide range from environmental and sensing applications to AI, automation, and IoT, with a rate of 16.75% on the horizontal axis. The vertical axis reflects the progress from basic research to advanced technologies, with a rate of 6.72%. Under the heading of Key Trends, methods such as "Deep Learning" and "Optimizations" in AI and Automation emphasize the connections between different areas - technologies such as IoT and 5G show effective application areas in literature.

Figure 9 (b) examines the conceptual structure of the studies through the connections established between thematic clusters. Topics including “military vehicles”, “aircraft detection”, “deep learning” and “motion planning” in the blue area shows the most critical role of UAVs in the defense industry. Al-Turjman et al. (2020) and Yazici et al. (2023) have demonstrated the strategic importance of UAVs’ huge data transfer and object detection abilities in military operations. Also, studies such as Abdulsalam et al. (2023) and Zaid et al. (2024) have shown that deep learning algorithms have a very important place, especially in the development of various autonomous functions. Concepts such as “remote sensing” and “photogrammetry” in the same cluster reflect the relationship between civilian applications and military reconnaissance activities and connect to topics like agriculture and environmental monitoring which also addressed by Uysal et al. (2015) and Yaprak et al. (2018).

Figure 9. Conceptual Structure Mapping of UAV Research Themes and Subtopics.

Terms like “controllers,” “flight control systems” and “optimization” seen in the red zone focus on the technical design and development of control mechanisms of UAVs. While Altan & Hacıoğlu (2020) focused on the contribution of control algorithms to UAV stability, Pehlivanoglu (2012) detailed the role of route optimization in increasing operational efficiency. The fact that words such as “Matlab” and “flight simulators” belong to this category implies the level of design, and simulation steps involved in control system development. The green area covers energy efficiency and communications infrastructure of UAV systems. Important words such as “5G mobile communication system”, "intelligent systems" and “energy efficiency” justify the integration of communications and energy management technologies into UAV systems, investigated by Alshaibani et al. (2022) and Hamamreh et al. (2019). In addition, the presence of the term “vehicle-to-vehicle communications” shows the potential of UAVs in collaborative systems.

Based on the bibliometric analyses conducted, the study identifies several key findings. Both Turkey and Russia have demonstrated notable growth in UAV-related scientific output, with Turkey’s research activity significantly accelerating after 2016, driven by geopolitical challenges and strategic objectives aimed at achieving defense independence. In contrast, Russia maintained a steadier growth trajectory, with an early emphasis on communication technologies. Strategic differences between the two countries are evident: Turkey’s research increasingly focuses on the integration of artificial intelligence, 5G networks, and dual-use military and civilian applications, while Russia concentrates on strengthening communication infrastructure and enhancing operational precision. Additionally, emerging technological themes such as deep learning, motion planning, and environmental monitoring are reshaping the UAV research landscape in both contexts. Collaboration network analyses further reveal that although domestic partnerships dominate in both countries, Turkey exhibits broader international engagement, indicating a more globally oriented research approach compared to Russia.

5. Discussion and Conclusion

This research establishes Turkiye and Russia's technological development gaps, technological advancement, strategic aims, and industries' application of UAVs. Even with both nations' considerable efforts in studying UAVs, the both of them have moved through a path under a disparate reality of national capabilities, national aspirations, and geopolitics.

Russia nailed a leading position in military UAV technologies, they focus on swarm control systems, ultra-reliable low-latency communication (uRLLC), and energy-efficient designs (Izhboldina and Lebedev 2023; Kapitonov et al. 2017). Such development cycle aligns with Russia's defense-oriented strategy for secure data transfer and increased battlefield capability. The accent of words such as "antennas" and "remote sensing" in Russian UAV studies highlights how critical it is for it to make communication security, airspace monitoring, and operational precision priorities (Zhukov et al. 2017). Also, the saturation of research outputs after 2021 (Podlesnykh et al. 2024) may indicate that Russia has shifted its focus or that innovations in this area have reached a stage of diminishing returns.

However, Turkiye has managed to integrate UAV technologies into a two faceted approach of the military and civilian sides. Adding artificial intelligence, 5G networks, and optimisation methods, it has developed multifunctional platforms such as Bayraktar TB2 and ANKA. These platforms are deployed for various purposes like disaster response, agriculture, and infrastructure monitoring (Abdulsalam et al., 2023; Yazici et al., 2023). The significant hype in UAV related publications after 2016 is directly related to Turkiye's response to geopolitical challenges and its goal of technological independence in the defense industry. However, despite the interdisciplinary focus, Turkiye's research on energy efficiency and control mechanisms is relatively limited, indicating that there is room for further development (Altan & Hacıoğlu, 2020; Uysal et al., 2015).

In competition between both countries in technological capabilities in such defense technology areas such as energy management and swarm management and general sectors of general research in comparison with Turkiye's success in developing state-of-the-art technology in artificial intelligence and deep learning for civilian and defense use, reflects inner and geopolitical requirements in technological development. Turkiye's growing use of civilian sectors such as agricultural yields and environment observation in comparison with a practically purely defense-related orientation in Russia and reflects competing future conceptions for UAV technology (Gyrichidi et al. 2024; Tahir et al. 2023).

The findings of this work have implications for international development of UAVs, in a larger context, too. Russia can reorient its direction of work towards civilian use of its capabilities in secure and efficient technology and contribute towards worldwide concerns such as disaster management or climate change, for instance. Turkiye, for its part, can develop its technological base through filling gaps in basic control and efficiency in terms of energy and become a developing world pioneer in terms of UAV technology.

Both countries have, in conclusion, been remarkably successful in terms of UAV-related R&D work. Wherein its overall orientation is monofocal in terms of its orientation towards industries and sectors, Turkiye's orientation is multidimensional and balanced in terms of its overall orientation towards sectors and industries. By overcoming its weaknesses discussed and taking its cross-sectoral utilizations, Russia and Turkiye will not only maintain its leadership in terms of UAV technology but contribute towards developing secure and sustainable worldwide networks, too.

Future research could extend the findings of this study by focusing on cross-national collaboration networks, technology transfer mechanisms, and the influence of emerging fields such as AI-driven swarm management on the UAV ecosystem. It is important to acknowledge that the present findings are limited by the scope of the Scopus database and the selected publication timeframe; thus, future studies may benefit from incorporating additional data sources and employing longitudinal bibliometric tracking to capture evolving trends more comprehensively. Additionally, the divergent trajectories observed between Turkey and Russia in UAV development could be further explored through the lens of innovation system theories and national security policy frameworks, providing deeper theoretical insights into the underlying drivers of technological advancement in each country.

Authors' contributions

MA: Writing, editing. OO: Application, writing, editing. All author(s) read and approved the final manuscript.

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Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

The author declares that they have no conflict of interest.

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4D Printing Technology and Its Application Possibilities in Unmanned Aerial Vehicles (UAVs)

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Abstract

4D printing technology is an innovative manufacturing method that adds the dimension of time to traditional 3D printing, enabling materials to respond to environmental stimuli (such as temperature, humidity, light, etc.) by changing shape, properties, or functionality. This study examines the fundamental principles of 4D printing in detail and explores its advantages and potential applications in the context of Unmanned Aerial Vehicles (UAVs). The foundation of 4D printing lies in the use of smart materials such as shape-memory polymers, self-healing composites, and hydrogels. These materials allow UAV components to dynamically adapt to flight conditions through pre-programmed responses. The study also comparatively discusses 4D printing techniques (FDM, SLA, DIW, SLM) and their suitability for UAV manufacturing. Additionally, current challenges such as material limitations, the complexity of multi-material printing, and high costs are addressed, and future research directions are highlighted. In conclusion, 4D printing technology holds revolutionary potential for improving UAV performance and durability. However, to fully realize this potential, advancements in material science, printing technologies, and design methods must continue.

Keywords: 4D printing, UAVs, smart materials, additive manufacturing.

4D Baskı Teknolojisi ve İnsansız Hava Araçlarındaki (İHA) Uygulama Olanakları

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Özet

4B baskı teknolojisi, geleneksel 3B baskıya zaman boyutunu ekleyerek malzemelerin çevresel uyaranlara (sıcaklık, nem, ışık vb.) tepki vererek şekil, özellik veya işlev değiştirmesine olanak tanıyan yenilikçi bir üretim yöntemidir. Bu çalışma, 4B baskının temel ilkelerini detaylı bir şekilde inceleyerek, İnsansız Hava Araçları (İHA'lar) bağlamında sunduğu avantajları ve uygulama potansiyellerini araştırmaktadır. 4B baskının temelini, şekil hafızalı polimerler, kendini onaran kompozitler ve hidrojeller gibi akıllı malzemelerin kullanımı oluşturur. Bu malzemeler, önceden programlanmış tepkiler sayesinde İHA bileşenlerinin uçuş koşullarına dinamik olarak uyum sağlamasını mümkün kılar. Çalışmada, 4B baskı teknikleri (FDM, SLA, DIW, SLM) ve bu tekniklerin İHA üretimindeki uygunlukları karşılaştırmalı olarak ele alınmıştır. Bunun yanı sıra, malzeme sınırlamaları, çoklu malzeme baskısının karmaşıklığı ve yüksek maliyet gibi mevcut zorluklar tartışılarak, gelecekteki araştırma yönleri vurgulanmıştır. Sonuç olarak, 4B baskı teknolojisi, İHA'ların performansını ve dayanıklılığını artırmada devrim niteliğinde bir potansiyele sahiptir. Ancak bu potansiyelin tam olarak gerçekleştirilebilmesi için malzeme bilimi, baskı teknolojileri ve tasarım yöntemlerindeki gelişmelerin sürdürülmesi gerekmektedir.

Anahtar Kelimeler: 4D baskı, İHA'lar, akıllı malzemeler, katmanlı üretim.

1. Fundamental Principles of 4D Printing

4D printing represents an innovative evolution in additive manufacturing by incorporating the dimension of time into the fabrication process, allowing printed objects to change their shape, properties, or functionality in response to external stimuli. This technology builds upon the principles of 3D printing by incorporating smart materials, such as shape-memory polymers, hydrogels, or responsive composites, which are programmed to react to environmental triggers like temperature, light, or humidity (Ryan et al., 2021). The fundamental principle of 4D printing lies in the precise design and programming of these materials to achieve predictable, controlled transformations over time, distinguishing it from static 3D-printed objects (Mitchell et al., 2018). This dynamic capability opens new possibilities for applications requiring adaptability, such as self-assembling structures, biomedical devices, and aerospace components. In this section, we provide a detailed overview of 4D printing, its core principles, and its significance in advancing manufacturing technologies.

Technological advancements in additive manufacturing have led to significant innovations in various fields, including aerospace, medicine, and robotics. Among these advancements, 4D printing technology has emerged as a revolutionary production method that builds upon the foundation of 3D printing by incorporating the time dimension. Unlike conventional 3D-printed objects, which remain static after fabrication, 4D-printed objects have the ability to change their shape, properties, or functionality in response to external stimuli such as temperature, light, magnetic fields, humidity, pH levels, or electrical signals (Bodaghi, Mahdi et al., 2024; Khan et al., 2022; Raina et al., 2021). This transformation is enabled by integrating smart materials with 3D printing techniques, allowing the production of adaptive and reconfigurable structures (Bai & Bu, 2022; Mallakpour et al., 2021; Momeni et al., 2017; Shinde et al., 2023). For instance, a study by Bodaghi et al. demonstrated the use of shape memory polymers in 4D printing to create self-folding structures that activate under thermal stimuli, showcasing the technology's potential for programmable transformations (Bodaghi et al., 2016).

The concept of 4D printing was first introduced by Skylar Tibbits in a TED talk in 2013, where he emphasized its potential to revolutionize manufacturing by enabling dynamic structures that evolve over time (Patil & Sarje, 2021). Since then, this technology has attracted widespread attention from academic researchers and industrial sectors. The primary motivation behind 4D printing is to overcome the limitations of 3D printing in producing static, rigid objects. By utilizing smart materials that respond to environmental stimuli, 4D printing enables objects to undergo programmed transformations, thus simplifying design, production, and assembly processes (Subeshan et al., 2021; Wang et al., 2023). A notable example is the work of Gladman et al., who developed hydrogel-based 4D-printed structures mimicking plant-inspired architectures that bend and twist in response to humidity changes, highlighting the precision of stimulus-responsive designs (Gladman et al., 2017).

UAV design faces persistent engineering constraints, including rigid structural configurations that hinder aerodynamic adaptability, weight limitations that affect flight efficiency and payload capacity, and vulnerability to damage in complex environments. Traditional materials and design strategies often require complex mechanical systems to achieve reconfigurability, which add to the overall weight and energy consumption. Additionally, operational environments such as high turbulence, extreme temperatures, or physical impacts necessitate materials that can dynamically respond or self-recover to maintain performance. These challenges highlight the need for smart materials capable of adaptive behaviour, which can be realized through 4D printing technologies.

UAVs, commonly known as drones, have witnessed remarkable advancements in recent years. These autonomous systems are widely used in military, commercial, and research applications, ranging from surveillance and reconnaissance to disaster response and cargo delivery. However, UAVs face several challenges, such as structural adaptability, weight optimization, and durability in dynamic environments. Conventional UAV structures rely on fixed materials that limit their ability to adapt to changing conditions, thereby restricting their efficiency and operational lifespan (Leist & Zhou, 2016; Li, S., 2023).

The integration of 4D printing technology into UAV design and manufacturing presents a promising solution to these challenges. By leveraging smart materials capable of self-adjustment, UAV components can be designed to morph, self-heal, and enhance aerodynamic performance based on environmental factors. For example, wings fabricated using 4D printing could adjust their shape in response to airflow changes, optimizing lift and manoeuvrability without the need for additional mechanical components

(Antezana et al., 2023; Sahafnejad-Mohammadi et al., 2022). Similarly, 4D-printed self-healing materials could enhance UAV durability by repairing minor damages autonomously, thus reducing maintenance costs and extending operational longevity (Saritha & Boyina, 2021).

Various additive manufacturing techniques, such as Fused Deposition Modelling (FDM), Stereolithography (SLA), Direct Ink Writing (DIW), and Selective Laser Melting (SLM), have been explored for 4D printing applications (Ryan et al., 2021). Each of these methods offers distinct advantages depending on the material properties and functional requirements of UAV components. Furthermore, advancements in computational design tools and simulation software, such as Autodesk Project Cyborg, facilitate the modelling and optimization of 4D-printed UAV structures, enabling engineers to predict and refine their behaviour before fabrication (Zhao et al., 2023).

As 4D printing technology continues to evolve, its potential to transform UAV manufacturing becomes increasingly evident. By enabling dynamic, adaptive, and multifunctional structures, this technology paves the way for next-generation UAVs that are lighter, more efficient, and capable of operating in complex environments. This paper explores the fundamental principles of 4D printing, its underlying smart materials, and its application possibilities in UAVs. Additionally, the challenges and prospects of integrating 4D printing in UAV design will be discussed, highlighting its potential to revolutionize the aerospace industry.

2. 4D Printing Techniques

4D printing refers to additive manufacturing processes that enable smart materials to change their shape or properties over time, with various 3D printing techniques such as FDM, DIW, SLA, and SLM being of critical importance in this field (Figure 1). FDM falls under the category of material extrusion and operates on the principle of heating and depositing thermoplastic or thermoset polymer filaments layer by layer. Commonly used thermoplastics such as PLA, and particularly Shape Memory Polymers (SMPs), are frequently employed for 4D printing applications (Fu et al., 2022; Joharji et al., 2022). Composites such as CNT/PLA filaments have been printed using FDM for electro-active shape recovery through Joule heating. Various SMP materials, including PLA/PCL and TPU/PLA/CNT, have also been utilized. The advantages of FDM include ease of processing, cost-effectiveness, recyclability of products, and a wide range of material options (Fu et al., 2022). Its disadvantages include low resolution (~100 µm), poor surface quality, the need for post-processing, and inferior mechanical properties; print resolution can be influenced by parameters such as raster angle and build orientation (Joharji et al., 2022; Khorsandi et al., 2021). It has been utilized in various applications, including prosthetics, implants, and automotive components (Megdich et al., 2023). Additionally, it is also suitable for producing bone scaffolds using porous PLA structures formed with chemical foaming agents or by combining PLA with alginate hydrogel (Khalid et al., 2022). DIW is a material extrusion technique that typically involves by depositing liquid or paste-like inks (photo- or thermo-curable) under pressure. It is a highly sought-after method, particularly for 4D printing of Liquid Crystal Elastomers (LCEs), and can be used with various inks containing polymer, ceramic, or metal particles (Fu et al., 2022). Azobenzene-functionalized LCEs are light-sensitive and undergo shape transformation upon exposure to light. Disk and log-pile structures printed via DIW can exhibit shrinkage with increasing temperature. The flexibility in material selection and the capability to print multiple materials are among the key advantages of this method (Joharji et al., 2022). The disadvantages of DIW include low print quality, reduced resolution, and difficulties in printing complex 3D geometries. Its potential has been highlighted in the fields of biomimetic components, robotics, electronics, and biomedical engineering. DIW has also been employed to fabricate shape-shifting structures using biodegradable shape memory polymers (Fu et al., 2022). Porous magnetic structures composed of TPU and NdFeB composite powders have been designed using DIW for self-powered electromagnetic devices. SLA falls under the category of vat photopolymerization and offers high resolution and good print quality by polymerizing liquid photocurable resins layer by layer using UV lasers or light. It is one of the most popular 4D printing techniques after material extrusion. It is suitable for 4D printing of SMPs, hydrogels, and biodegradable smart polymers. SLA-based technology has been reported for the fabrication of biodegradable smart polymer materials in disposable UAV systems. DLP (Digital Light Processing), a technique like SLA, cures an entire layer simultaneously, which results in faster printing and higher throughput; DLP has been used for SMPs and hydrogels. The high-resolution Projection Micro Stereolithography technique is also derived from SLA and is used for printing SMP-based microstructures. The disadvantages of SLA include resin waste, higher cost compared to other methods, and the need for careful handling due to photosensitive monomers. However, methods such as FDM, which do not use resin, are suggested to potentially be safer with respect to residual monomers that may cause irritation (Khalid et al., 2022; Khorsandi et al., 2021). SLA and related techniques are also widely used in various biomedical and dental applications, such as dental ceramics, dental scaffolds, surgical guides, and prosthetics (Hada et al., 2020; Kruth et al., 2005). SLM (Selective Laser Melting) is one of the powder bed fusion techniques and forms layers by melting metal powders with a laser. It is particularly used for the fabrication of metal components. The advantages of SLM include its suitability for powder processing and high mechanical strength. However, its disadvantages are low dimensional accuracy and longer printing times. It has been employed in the 4D printing of shape memory alloys such as TiNi (Speirs et al., 2017). Additionally, it has also been used in biomedical applications—alongside Selective Laser Sintering (SLS)—for metal dental prostheses such as Co-Cr alloys, porous tantalum and titanium implants, and customized dental implants (Kruth et al., 2005). In general, each of these techniques has distinct material compatibilities, advantages, and disadvantages, and the selection of a particular method for a 4D printing application depends on factors such as the desired shape-morphing behavior, functionality, and material characteristics. For instance, the use of SLA-based technology in the fabrication of biodegradable smart polymer materials for disposable UAV wings can simplify production by enabling automated manufacturing, enhanced accuracy, minimal waste, and optimized cost/customization/structural integrity. Table 2 provides a comparative overview of these techniques, offering guidance to UAV designers on which method is suitable for specific applications.

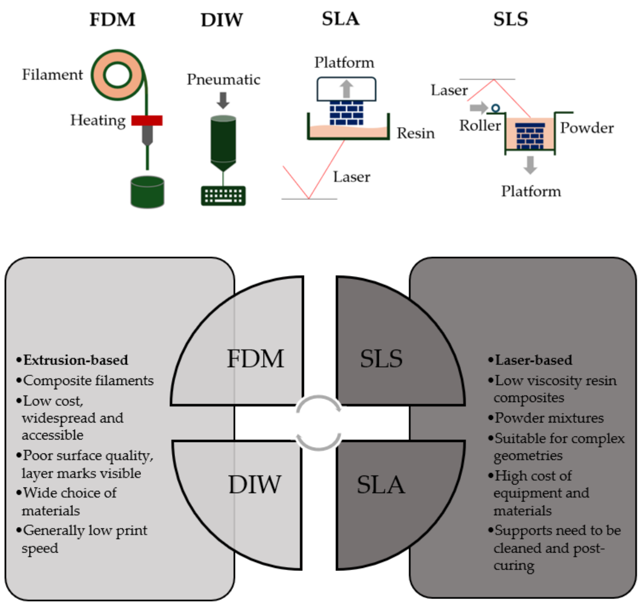

Figure 1. FDM, DIW, SLA and SLS printing techniques (Wu et al., 2025).

Table 2. Analysis of 4D Printing Techniques used in UAV Manufacturing (Frazier, 2014; Khoo et al., 2015; Lewis, 2006; Melchels et al., 2010).

Technique	Compatible Materials	Printing Speed	Suitability for UAV Components
FDM	SMPs, Thermoplastics	20–50 mm/s	- Suitable for adaptive wings and lightweight components -Low-cost prototyping
SLA	Photopolymers, Hydrogels	50–100 mm/s	- High precision for small components (e.g., sensor covers) - Smooth surfaces for aerodynamic parts
DIW	Self-Healing Composites, Hydrogels	5–20 mm/s	- Ideal for self-healing panels - Flexible and complex structures
SLM	SMAs, Metal Powders	10–40 mm/s	- Suitable for durable actuators and supports - High mechanical strength

3. Advanced Materials, Structural Adaptability, and Performance Innovations

The integration of 4D printing technology into UAVs opens new horizons in aerospace engineering, offering advancements in material selection, structural adaptability, aerodynamics, energy efficiency, and modularity. One of the fundamental aspects of 4D printing is the use of smart materials such as shape-memory polymers, self-healing composites, hydrogels, and SMAs. Schematic representation of the shape-memory effect is shown in Figure 2. However, not all 3D printing methods are equally suited for 4D printing, as the technology demands compatibility with stimuli-responsive materials and dynamic structural capabilities (Tibbits, 2014). For instance, while FDM is widely accessible, its reliance on thermoplastics like PLA or ABS limits its ability to process shape-memory polymers or hydrogels, which are critical for 4D-printed UAV components (Ge et al., 2013). Similarly, SLA excels in precision but struggles with flexible or biocompatible photopolymers, restricting its use in morphing wing applications (Zarek et al., 2015) These materials contribute to improved structural resilience, reducing maintenance requirements and enhancing UAV longevity by autonomously repairing minor damages (Ebeid & James, 2023; Lin et al., 2024). For example, Zang and colleagues developed a self-healing double-network shape memory polymer system suitable for high-resolution 4D printing. By incorporating linear polycaprolactone polymer into a methacrylate-based rigid SMP structure, they demonstrated that more than 90% of structural damage could be repaired (Zhang et al., 2019). The schematic representation of the self-healing mechanism is provided in Figure 3. The success of such applications hinges on selecting printing methods that preserve the stimuli-responsive properties of these materials, as traditional SLS—despite its durability—often produces static structures incompatible with dynamic 4D behaviours (Momeni et al., 2017).

Additionally, aerodynamic optimization plays a crucial role in UAV efficiency, where shape-morphing wings and airframes can reduce drag, improve lift, and optimize manoeuvrability in changing flight conditions. Additionally, aerodynamic optimization plays a crucial role in UAV efficiency, where shape-morphing wings and airframes can reduce drag, improve lift, and optimize manoeuvrability in changing flight conditions (Hoa et al., 2022). A notable study by Han et al. developed a shape-memory alloy-based morphing wing for UAVs to address aerodynamic inefficiencies during variable flight speeds. As a result, they achieved a 5.8% increase in lift-to-drag ratio at angles of attack above 5°, improving flight performance (Han et al., 2016).

Beyond aerodynamic benefits, 4D-printed UAVs can adapt their mission capabilities, enabling real-time shape transformation to accommodate different payloads and operational needs. This adaptability is particularly advantageous in military, search and rescue, and commercial applications where modular designs allow drones to switch functionalities seamlessly (Goh et al., 2017; Zaharia et al., 2023).

Furthermore, energy efficiency is significantly improved through innovations like adaptive solar panels, which optimize sunlight absorption based on UAV orientation, and morphing rotor blades that enhance propulsion efficiency (Chen et al., 2024).

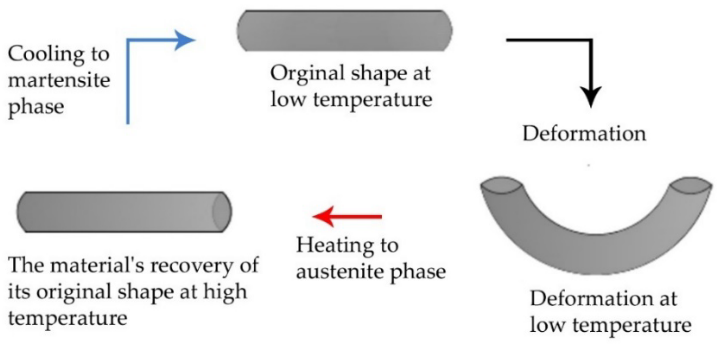

Figure 2. Macroscopic illustration of the phase transformation process in shape memory alloys.

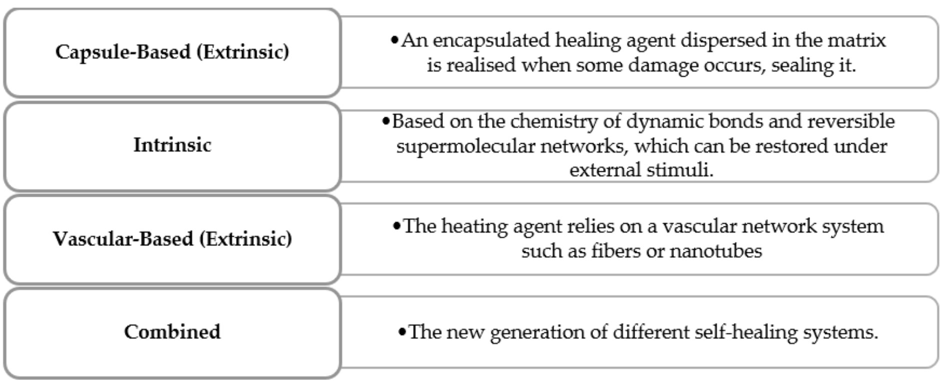

Figure 3. Self-healing mechanism.

Table 1. Properties of smart materials for 4D printing in UAV applications.

Material Type	Stimulus	Mechanical Strength	Density	Advantages in UAV Applications	Disadvantages in UAV Applications
Shape Memory Polymers (SMPs)	Heat, Light	10–100 MPa (Liu et al., 2007)	~1.2 g/cm³ (Huang et al., 2012)	- Shape morphing for adaptive wing structures -Aerodynamic optimization -Lightweight (Yan et al., 2023)	-Low environmental durability - Susceptible to repeated cyclic deformation (Yan et al., 2023)
Self-Healing Composites	Heat, Mechanical Stress	50–200 MPa (Heo et al., 2016; Norris et al., 2011)	~1.1 g/cm³ (Li, G., 2014)	- Autonomous crack repair - Extended lifespan - Reduced maintenance costs (Sabet, 2024; Tan et al., 2021)	- Long repair times (hours) - High production costs (Sabet, 2024)
Hydrogels	Moisture, pH	<1 MPa (Yin et al., 2013)	~1.3 g/cm³ (Cates, 2010)	- Lightweight and flexible -Biocompatibility -Environmental sensor integration (Chen et al., 2024)	- Low mechanical strength - Limited use in structural applications (Chen et al., 2024)
SMAs	Heat, Electrical	500–1000 MPa (Yi & Kim, 2021)	~6.5 g/cm³ (Chu et al., 2004)	- High strength/weight ratio - Fast response time - Actuator applications (Yi & Kim, 2021)	- High weight - Complex manufacturing process - High cost (Yi & Kim, 2021)

Another transformative aspect of 4D printing is the development of collapsible and self-assembling UAVs, which are highly beneficial for compact transportation and rapid deployment in inaccessible areas (Yi & Kim, 2021). These UAVs can be stored in minimal space and autonomously expand into their operational configurations when required. Moreover, in manufacturing, 4D printing revolutionizes UAV production by enabling rapid prototyping, cost-effective customization, and on-demand production of specialized UAV components (Ebeid & James, 2023). This innovation accelerates development cycles and reduces dependency on traditional manufacturing constraints.

Despite its immense potential, integrating 4D printing into UAV development still faces technological and material challenges. However, as research progresses, the refinement of printing techniques, enhanced computational modelling, and the discovery of new responsive materials will continue to push the boundaries of UAV innovation.

Overall, 4D printing has the potential to revolutionize UAV technology by enabling autonomous adaptation, enhanced durability, optimized flight performance, and mission-specific configurability. As highlighted by Gladman et al., the future of 4D-printed UAVs lies in merging advanced materials with scalable, high-precision printing methods to overcome current limitations (Sydney Gladman et al., 2016). The aerospace industry is poised to witness the emergence of next-generation UAVs that are lighter, smarter, and more efficient than ever before (Yan et al., 2023).

4. Challenges and Limitations in UAV Applications

The development of 4D printing technology is closely linked to advancements in smart materials. However, the variety of smart materials suitable for 4D printing is still limited. In UAV applications, there is a strong demand for lightweight, biocompatible, biodegradable, and durable smart materials. These materials must be capable of providing fast, consistent, and predictable responses to environmental stimuli while maintaining high mechanical strength. For instance, biocompatible and biodegradable materials are critical for UAVs used in ecological research, such as monitoring protected natural reserves, where components must degrade without leaving harmful residues to avoid disrupting delicate ecosystems. A concrete example is the work of Rajendran et al., who developed a biodegradable shape-memory polymer for 4D-printed UAV wing components for disposable UAV systems in environmental monitoring. Their material, a PLA-based composite, achieved complete biodegradation within approximately 1 year under natural conditions while enabling thermally triggered shape morphing for adaptive flight, thus ensuring minimal environmental impact (Ebeid & James, 2023). Some smart materials currently struggle to meet these requirements, leading to concerns about their long-term stability and durability (Khare et al., 2017; Pei & Loh, 2018; Ryan et al., 2021)

Furthermore, the integration of multiple materials in a single 4D-printed UAV component introduces additional challenges. Combining different materials in the same printing process can lead to compatibility issues, adhesion problems, and difficulties in controlling material reactions. This complexity requires further research into multi-material 4D printing techniques and the development of new material combinations specifically designed for UAV applications (Khare et al., 2017; Pei & Loh, 2018; Ryan et al., 2021).

Despite the broad application potential offered by 4D printing technology in UAVs, it faces certain challenges and limitations. These challenges range from technological constraints to material limitations and barriers in manufacturing processes. Addressing these issues is crucial for the successful integration of 4D printing into UAV development and production.

The effectiveness of 4D printing techniques in UAV manufacturing depends on factors such as material compatibility, speed, and cost of the selected method. 4D printing requires precise control of the shape-changing processes of printed objects. This control is achieved by accurately adjusting the material properties, environmental stimuli, and printing parameters. Therefore, 4D printing systems need more complex and sophisticated control mechanisms. Although existing 4D printing technologies are generally suitable for small-scale prototypes and specialized applications, they still face challenges in large-scale production. In the UAV industry, scalability issues must be resolved to enable the widespread adoption of 4D-printed components in commercial and military drones (Pei & Loh, 2018).

Another major technological limitation is the need for advanced software tools to accurately simulate the behaviour of 4D-printed objects and optimize designs. Existing software often struggles to model complex geometries and multi-material interactions, making it difficult to predict how 4D-printed UAV components will behave under different conditions. More sophisticated and user-friendly simulation tools must be developed to improve design precision and efficiency (Pei & Loh, 2018).

Not all existing 3D printing methods are suitable for 4D printing. Some conventional printing techniques are unable to process certain types of smart materials or support shape-changing processes that require precise control. As a result, new printing methods specifically designed for 4D printing applications must be developed. For UAV manufacturing, this includes optimizing printing techniques to produce aerodynamically efficient, lightweight, and structurally resilient components. Additionally, 4D printing processes can be time-consuming, particularly for complex geometries and multi-material applications. This can significantly increase production costs and limit industrial-scale applicability. Improving printing speeds and enhancing manufacturing efficiency are critical for making 4D printing a viable solution for UAV production. Moreover, errors that occur during the printing process can negatively impact the shape-changing performance and durability of UAV components. To address this, advanced control systems and real-time process monitoring techniques must be implemented to improve print quality and reliability (Bodaghi, et al., 2024; Pei & Loh, 2018; Ryan et al., 2021).

5. Application Areas and Potential Usage Scenarios in UAVs

One of the most promising applications of 4D printing in UAVs is the development of adaptive wing structures. Traditional UAV wings are static and designed for specific flight conditions. However, with 4D printing, wings can be engineered to change shape in response to environmental factors such as wind speed, temperature, or altitude. This adaptability can improve aerodynamic efficiency, reduce energy consumption, and extend the flight range of UAVs. For instance, wings that adapt their shape mid-flight to improve lift and reduce drag can greatly boost the efficiency of long-endurance drones deployed for surveillance or delivery tasks (Bai & Bu, 2022; Li, S., 2023).

Another significant advantage of 4D printing is its ability to enable the production of self-assembling UAVs, which can be particularly useful in military applications or disaster response scenarios. These UAVs can be compactly stored and transported, and upon deployment, they can automatically assemble into their operational form. This capability is crucial for rapid deployment in remote or inaccessible areas where traditional assembly methods are impractical, offering a practical solution for time-sensitive missions (Li, 2023; Wang et al., 2023).

In addition to structural adaptability, 4D printing facilitates the use of lightweight yet durable materials, which are essential for maximizing UAV payload capacity and flight efficiency. Smart materials produced through 4D printing can be both lightweight and capable of self-healing or adapting to stress. For instance, a UAV frame made from self-healing materials can repair minor damage incurred during flight, thereby increasing the lifespan and reliability of the drone and reducing maintenance needs (Momeni et al., 2017; Raina et al., 2021; Sahafnejad-Mohammadi et al., 2022).

Energy efficiency is another area where 4D printing can make a substantial impact on UAV performance. This technology can be used to create energy-efficient components, such as adaptable solar panels, which can change their shape and orientation to maximize sunlight absorption. Such panels can extend the flight time of solar-powered drones, making them particularly beneficial for long-duration missions like environmental monitoring or border surveillance (Li, S., 2023; Sahafnejad-Mohammadi et al., 2022).

Furthermore, 4D printing enables the production of customizable payload systems, addressing the diverse needs of UAV missions. UAVs often need to carry different types of payloads depending on their objectives, and 4D printing allows for payload systems that can adapt to various shapes and sizes. For example, a UAV designed for agricultural monitoring can have a payload system that adjusts to carry different sensors or cameras, depending on the specific requirements of the mission, enhancing operational flexibility (Aldawood, 2023; Sahafnejad-Mohammadi et al., 2022; Saritha & Boyina, 2021).

As 4D printing technology continues to evolve, its potential to transform UAV manufacturing becomes increasingly evident. By enabling dynamic, adaptive, and multifunctional structures, this technology paves the way for next-generation UAVs that are lighter, more efficient, and capable of operating in complex environments. This paper further explores the fundamental principles of 4D printing, its underlying smart materials, and its application possibilities in UAVs, while also discussing the challenges and prospects of integrating 4D printing into UAV design, highlighting its potential to revolutionize the aerospace industry.

The high cost of 4D printing technology currently limits its commercial applicability in UAV manufacturing. Smart material costs, specialized printing equipment, and the development of advanced software tools contribute to the overall expense of the technology. To facilitate broader adoption, research is needed to make 4D printing more cost-effective by optimizing material production, reducing waste, and improving printing efficiency. Finally, 4D printing requires a different set of knowledge and skills compared to traditional design and engineering approaches. UAV designers must have a deep understanding of smart materials, environmental interactions, and 4D printing processes. Therefore, specialized training programs and interdisciplinary research efforts are essential to build expertise in 4D printing applications for UAVs. Developing a workforce proficient in this technology will be key to overcoming current challenges and unlocking its full potential in UAV development (Bodaghi, Mahdi et al., 2024; Pei & Loh, 2018; Ryan et al., 2021).

6. Conclusion

4D printing represents a groundbreaking advancement in additive manufacturing, offering unparalleled opportunities for creating adaptive and multifunctional UAV structures through the integration of smart materials. This study underscores the technology’s potential to revolutionize aerospace engineering by enabling UAVs with adaptive aerodynamics, self-assembling capabilities, self-healing components, and energy-efficient designs, thereby enhancing operational efficiency and longevity. However, significant challenges, including the limited availability of lightweight and durable smart materials, complexities in multi-material printing processes, and high production costs, currently impede its widespread adoption. Overcoming these barriers requires sustained advancements in material science, printing technologies, and computational modelling, coupled with investment in interdisciplinary education to develop a skilled workforce. By fostering collaboration among material scientists, engineers, and industry stakeholders, 4D printing can unlock the full potential of next-generation UAVs, paving the way for smarter, more resilient, and sustainable autonomous flight solutions in both commercial and defense applications. In the future, the integration of AI-driven design algorithms into 4D printing processes may enable more precise prediction of material behaviors, opening new research avenues for the development of UAV systems that can intelligently respond to environmental stimuli.

Authors' Contribution

The authors declare that they have contributed equally to the article.

Conflict of Interest Statement

There is no conflict of interest among the authors.

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The study has been conducted in accordance with research and publication ethics

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Antik Kentlerin Giriş Kapılarının İnsansız Hava Araçları ile Üç Boyutlu Modellenerek Belgelenmesi: Anavarza Ören Yeri Zafer Kapısı Örneği

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Özet

Bu çalışma, Adana ili sınırlarında yer alan Anavarza Antik Kenti'ndeki üç kemerli Roma yapısı Zafer Kapısı'nın İnsansız Hava Aracı (İHA) tabanlı fotogrametri yöntemiyle üç boyutlu (3B) olarak belgelenmesini ve üretilen dijital modelin geometrik doğruluğunun analiz edilmesini amaçlamaktadır. Çalışmada, yapıdan modele fotogrametrik iş akışı kapsamında 220 adet yüksek çözünürlüklü görüntü Agisoft Metashape yazılımında işlenmiş; nokta bulutu, mesh model ve ortofoto üretimi gerçekleştirilmiştir. Modelin konumsal doğruluğunun artırılması amacıyla altı adet Yer Kontrol Noktası (YKN) ile aerotriangülasyon yapılmış, modelin harici doğrulaması altı adet Kontrol Noktası (KN) üzerinden gerçekleştirilmiştir. Doğruluk analizi sonucunda ortalama kök-ortalama kare hata (RMSE) değeri 0.027 m olarak hesaplanmış; bu sonuç, yapı ölçeğinde yüksek geometrik doğrulukta bir model elde edildiğini göstermektedir. Elde edilen 3B model, Zafer Kapısı'nın taş işçiliği, kemer geometrisi ve mevcut fiziksel durumu gibi mimari detayları hassas biçimde temsil etmektedir. Çalışma ayrıca fotogrametri tabanlı belgelenme sürecinde karşılaşılan ışık koşulları, yüzey dokusu, örtüşme oranı ve uçuş planlaması gibi teknik zorluklara da metodolojik çözüm önerileri sunmaktadır. Sonuçlar, İHA tabanlı fotogrametri yöntemlerinin, özellikle büyük ölçekli ve mimari olarak karmaşık kültürel miras yapılarının belgelenmesinde yüksek doğruluk, zaman ve maliyet etkinliği sağladığını göstermektedir. Elde edilen 3B modelin dijital arşivleme, restorasyon planlaması, sanal sergi ve eğitim gibi alanlarda çok amaçlı olarak kullanılabileceği vurgulanmakta; çalışma, kültürel mirasın dijital dönüşümüne yönelik uygulamalı bir örnek sunmaktadır.

Anahtar Kelimeler: Anavarza Zafer Kapısı, insansız hava araçları, üç boyutlu modelleme, arkeolojik belgelenme, dijital kültürel miras.

Documentation of Ancient Cities' Entrance Gates by Using Three-Dimensional Models with Unmanned Aerial Vehicles: Anavarza Archaeological Site Victory Gate Example

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Abstract

This study aims to document and generate a three-dimensional (3D) digital model of the Triumphal Arch located within the ancient city of Anavarza, Adana Province, Türkiye, using Unmanned Aerial Vehicle (UAV)-based photogrammetric methods. A total of 220 high-resolution images were processed in Agisoft Metashape following a Structure-from-Motion (SfM) workflow to produce dense point clouds, textured mesh models, and orthophotos. To enhance the spatial accuracy of the model, six Ground Control Points (GCPs) were integrated during the aerial triangulation phase, and the external accuracy was assessed using six independent Check Points (CPs). As a result of the accuracy assessment, the Root Mean Square Error (RMSE) was calculated as 0.027 m, demonstrating that the generated 3D model achieves high geometric precision at the architectural scale. The model effectively preserves and visualizes architectural features such as masonry details, arch curvature, and structural deformations. Moreover, this study discusses several technical challenges encountered during the documentation process, including lighting conditions, surface texture complexity, image overlap ratio, and flight planning, and offers practical solutions for each. The results indicate that UAV-based photogrammetry offers a fast, cost-effective, and highly accurate alternative for documenting large-scale and architecturally complex cultural heritage sites. The resulting 3D model provides a valuable digital record that can be utilized for archival preservation, restoration planning, virtual exhibitions, and educational purposes. This work serves as an applied example of digital heritage documentation, contributing to the broader discourse on the digital transformation of cultural heritage.

Keywords: Anavarza Victory Gate, unmanned aerial vehicles, three-dimensional modeling, archaeological documentation, digital cultural heritage.

1. Giriş

Kültürel miras alanlarının belgelenmesi, günümüz teknolojilerinin sunduğu imkânlarla yeniden tanımlanmakta; özellikle arkeolojik yapılar, üç boyutlu dijital modeller aracılığıyla hem bilimsel analizlere hem de koruma planlamalarına konu olmaktadır. Bu çalışma, Adana ili sınırlarında yer alan ve Roma döneminin en görkemli yapılarından biri olan Anavarza Zafer Kapısı'nın İnsansız Hava Aracı (İHA) tabanlı görüntülerle belgelenerek üç boyutlu modellenmesini amaçlamaktadır.

Geliştirilen yöntem, geleneksel ölçüm tekniklerine alternatif olarak dijital belgelenmenin sağladığı avantajları ortaya koymakta ve kültürel mirasın sürdürülebilirliği açısından önemli bir katkı sunmaktadır.

Çalışmanın bilimsel özgünlüğü, Zafer Kapısı gibi çok kemerli ve yüksek yapısal kompleksiteye sahip bir mimari unsurun fotogrametrik modelleme süreçlerini ayrıntılı biçimde ele alması; üretilen modelin doğruluğunu yer kontrol noktaları (YKN) ve kontrol noktaları (KKN) yardımıyla sayısal olarak değerlendirmesiyle pekiştirilmektedir. Ayrıca modelleme sürecinde karşılaşılan teknik zorluklar ve çözüm önerileri de tartışılarak, benzer projelere metodolojik rehberlik sağlanması hedeflenmektedir.

Bu kapsamda, giriş bölümü aşağıdaki alt başlıklarla yapılandırılmıştır:

1.1. Antik Kentlerin ve Giriş Kapılarının Önemi: Kültürel mirasın belgelenmesinde giriş kapılarının simgesel ve tarihsel anlamı aktarılmakta; çalışmanın tematik çerçevesi kurulmaktadır.

1.2. Anavarza Ören Yeri ve Zafer Kapısı: Çalışma alanı olan Anavarza Ören Yeri'nin tarihsel arka planı sunulmakta, Zafer Kapısı'nın mimari özgünlüğü açıklanmaktadır.

1.3. Geleneksel Belgelenme Yöntemlerinin Sınırlamaları: Alanda yaygın olarak kullanılan klasik yöntemlerin sınırlılıkları örneklerle ele alınmakta; yeni teknolojilere duyulan ihtiyaç temellendirilmektedir.

1.4. İHA ve Üç Boyutlu Modelleme: İHA teknolojisinin arkeolojik belgelenmedeki artan rolü vurgulanmakta, alana ilişkin güncel literatür katkılarıyla desteklenmektedir.

1.5. Üç Boyutlu Modelleme Teknolojileri: Çalışmada kullanılan fotogrametrik modelleme teknolojileri tanıtılmakta, seçilen yazılımların özellikleri ile bilimsel gerekçeleri açıklanmaktadır.

Bu alt başlıklar aracılığıyla, çalışma yalnızca belirli bir yapının modellenmesi değil; aynı zamanda dijital belgelenme sürecinin bütüncül bir değerlendirmesini de sunmayı amaçlamaktadır.

1.1. Antik Kentlerin ve Giriş Kapılarının Önemi

Antik kentler, geçmiş uygarlıkların sosyal, kültürel, ekonomik ve mühendislik bilgilerini yansıtan eşsiz mekânlardır. Bu kentler, yalnızca birer yaşam alanı değil, aynı zamanda dönemin toplumsal düzenini, dinsel ritüellerini ve politik yapısını temsil eden kompleks yerleşimlerdir (Akurgal, 2000). Bu bağlamda, antik kentlerin giriş kapıları, yalnızca mimari bir unsur değil; aynı zamanda kentin kimliğini, siyasi gücünü ve estetik anlayışını yansıtan simgesel yapılar olarak değerlendirilmektedir (Avrami, 2000).

Tarihsel bağlamda giriş kapıları, çoğu zaman zafer anıtları veya sınır belirleyici yapılar olarak işlev görmüştür. Özellikle Roma döneminde inşa edilen kapılar, çok kemerli, yüksek oranlı ve zengin süslemeli yapılarıyla dikkat çeker. Bu mimari öğeler, dönemin teknik kapasitesini ve mühendislik becerisini ortaya koyarken; bir yandan da sosyal prestij ve otoriteyi görünür kılmayı hedeflemiştir (Campana, 2017). Aynı zamanda bu yapılar, tören geçitleri, ticari giriş-çıkış kontrolü ve kentsel organizasyonun temel bileşenlerinden biri olarak işlevsel roller üstlenmiştir.

Ancak günümüzde, bu yapılar hem doğal afetler hem de insan müdahalesi nedeniyle ciddi yıpranmalara maruz kalmaktadır. Koruma ve restorasyon faaliyetleri genellikle geleneksel tekniklerle yürütülmekte olup, birçok ayrıntının belgelenmesinde yetersiz kalınabilmektedir (Balcı & Ulvi, 2024). Bu noktada dijital modelleme teknikleri, giriş kapılarının hem görsel hem de metrik anlamda eksiksiz biçimde belgelenmesini ve geleceğe taşınmasını mümkün kılmaktadır.

Bu bağlamda, Anavarza Zafer Kapısı gibi hem tarihsel hem de mimari açıdan yüksek değere sahip yapılar için İHA ile desteklenen üç boyutlu modelleme yöntemleri, çok katmanlı bir belgelenme ve analiz süreci sunmaktadır. Bu çalışmada, söz konusu yapının belgelenmesine yönelik dijital yaklaşımlar kullanılmış; elde edilen bulgular doğrultusunda hem bilimsel hem de kültürel miras yönetimine katkı sağlanması amaçlanmıştır (bkz. 1.2, 1.4).

1.2. Anavarza Ören Yeri ve Zafer Kapısı

Anavarza Antik Kenti, Adana ili Kozan ilçesi sınırları içerisinde yer almakta olup, Anadolu'nun tarihsel katmanlarını barındıran en önemli arkeolojik alanlardan biridir. Kentin geçmişi Roma dönemine uzanmakta, sonraki Bizans, Ermeni Krallığı ve İslam dönemlerine ait izler de kapsamlı biçimde izlenebilmektedir (Erten, 2018). Anavarza, antik dönemde "Caesarea ad Anazarbus" ismiyle anılmış ve özellikle Roma İmparatorluğu döneminde Kilikya bölgesinin idari ve askeri merkezi konumuna gelmiştir. Kentte yer alan surlar, tiyatro, stadyum, bazilika, su kemerleri ve hamam gibi yapılar, kentin gelişmiş kentleşme düzeyini ve mimari çeşitliliğini ortaya koymaktadır.

Anavarza'nın en dikkat çekici yapılarından biri olan Zafer Kapısı, kentin güneybatı girişinde yer almakta olup üç kemerli ve çok katmanlı yapısıyla tipik bir Roma zafer takı örneğidir. Mimarisi, Roma dönemine ait tekniklerin ve estetik anlayışın gelişmiş bir yansımasıdır. Kapı, yalnızca giriş–çıkış kontrolü sağlayan bir yapı değil, aynı zamanda siyasi bir mesaj taşıyan anıtsal bir semboldür. Özellikle çok kemerli tasarımı, dönemsel otoriteyi ve mimari kudreti simgelemektedir (Özdemir, 2015).

Mevcut literatürde, Zafer Kapısı üzerine yapılan çalışmalar genellikle yapının tarihi geçmişi, mimari üslubu ve restorasyon potansiyeline odaklanmıştır. Ancak, bu çalışmaların çoğu geleneksel ölçüm yöntemlerine dayanmaktadır. Ölçüm ve belgeleme faaliyetleri genellikle manuel tekniklerle sınırlı kalmış; yapının yüksekliği, taş işçiliği gibi kritik detaylar dijital olarak belgelenememiştir (Önal et al., 2023). Bu eksiklik, yapının hem mimari analizinde hem de restorasyon sürecinde ölçülebilir eksiklikler yaratmaktadır.

Bu çalışma ise, Zafer Kapısı'nın İHA ile çekilen yüksek çözünürlüklü görüntülerden elde edilen üç boyutlu fotogrametrik model aracılığıyla belgelenmesini amaçlamaktadır. Bu yaklaşım, yalnızca görsel temsil sunmakla kalmamakta; aynı zamanda yapının geometrik doğruluğunu değerlendirme ve uzun vadeli koruma süreçlerine katkı sağlama potansiyeli taşımaktadır. Kapının üst bölümleri, arşitrav ve alınlık kısımları gibi geleneksel yöntemlerle erişilmesi zor alanlar, İHA'lar aracılığıyla etkili şekilde belgelenmiş; modelleme süreci ile restorasyon simülasyonlarına uygun yüksek doğruluklu dijital veri setleri elde edilmiştir.

1.3. Geleneksel Belgelenme Yöntemlerinin Sınırlamaları

Arkeolojik yapıların belgelenmesi sürecinde uzun yıllar boyunca başvurulan geleneksel yöntemler; elle çizim, klasik fotoğrafçılık, elle alınan ölçümler ve manuel plan çıkarımı gibi teknikleri içermektedir. Bu yöntemler, belirli ölçüde görsel kayıt ve mimari analiz imkânı sunmuş olsa da özellikle büyük, karmaşık ve yüksek yapılar için çeşitli zorluklar barındırmaktadır (Remondino & El-Hakim, 2006).

Geleneksel ölçme teknikleri, ayrıntılı bir yapı analizi gerçekleştirmek için yoğun emek, zaman ve uzmanlık gerektirir. Özellikle anıtsal ve çok katmanlı mimari unsurlarda (örneğin çok kemerli giriş kapıları veya anıtsal zafer takları gibi) erişimi zor bölgelerin belgelenmesi, fiziksel engeller ve güvenlik riskleri nedeniyle çoğu zaman ya mümkün olamamakta ya da yetersiz verilerle sınırlı kalmaktadır (Kabadayı & Mumcuoğlu Türker, 2025; Kabadayı, 2021). Zafer Kapısı gibi yüksekliğe sahip bir yapının üst bölümlerine erişim, iskele kurulumu veya vinç desteği gerektirebilir ki bu da hem maliyetli hem de zamana bağlı bir süreçtir (Verhoeven, 2011).

Ayrıca, klasik yöntemlerle elde edilen belgeler (örneğin çizimler veya iki boyutlu fotoğraflar), yapıların hacimsel ilişkilerini, topoğrafik konumlarını veya geometrik deformasyonlarını yansıtmakta yetersiz kalabilmektedir. Bu durum, restorasyon ve koruma çalışmalarının doğruluğunu da doğrudan etkilemektedir. Örneğin bir kemerin yatay düzlemdeki eğimi veya bir taş bloğun eksenel kayması, yalnızca görsel belgelerle tam anlamıyla fark edilemeyebilir (Ulukok & Ulvi, 2023).

Ayrıca belgelerin standartlaşmasında da sorunlar yaşanabilmektedir. Farklı ekiplerin farklı dönemlerde yaptığı belgeler arasında tutarsızlıklar oluşabilir. Bu durum, özellikle uzun soluklu arkeolojik kazı ve restorasyon projelerinde ciddi koordinasyon eksikliklerine yol açabilir. Bu nedenle, yüksek doğrulukta, tekrarlanabilir ve dijital olarak saklanabilir belgeleme yöntemlerine olan ihtiyaç artmaktadır.

İşte bu noktada, İnsansız Hava Aracı (İHA) destekli üç boyutlu modelleme yöntemleri, hem belgeleme kalitesini hem de sürecin verimliliğini artırmak adına geleneksel yöntemlere önemli bir alternatif sunmaktadır. Bu çalışmanın önerdiği dijital yöntemler, geleneksel sınırlamaların üstesinden gelmeyi hedeflemekte ve arkeolojik belgelenme pratiğini çağdaş bir düzleme taşımaktadır.

1.4. İnsansız Hava Araçları (İHA) ve Üç Boyutlu Modelleme

Günümüzde arkeolojik yapıların belgelenmesinde İHA kullanımı giderek artan bir ivmeyle yaygınlaşmaktadır. Özellikle yüksek, geniş ve ulaşılması zor mimari unsurların belgelenmesinde İHA sistemleri, zaman ve emek açısından önemli bir avantaj sağlamaktadır. Bu bağlamda İHA'lar, sadece veri toplama aracı değil, aynı zamanda dijital belgeleme sürecinin merkezinde yer alan teknolojik bir bileşen haline gelmiştir (Campana, 2017; Verhoeven, 2011; Mumcuoğlu Türker & Kabadayı, 2025).

İHA'lar sayesinde yapıların tüm yüzeyleri farklı açılardan görüntülenebilmekte, kısa sürede çok sayıda yüksek çözünürlüklü görsel elde edilebilmektedir. Bu görüntüler, fotogrametrik iş akışları ile üç boyutlu modellere dönüştürülerek, yapıların hacimsel geometrisi, detaylı yüzey yapıları ve mevcut deformasyonları analiz edilebilmektedir (Remondino

& El-Hakim, 2006; Kabadayı et al., 2020). Bu çalışmada kullanılan İHA ile elde edilen görüntüler, Zafer Kapısı'nın üst kotlarındaki detayların da eksiksiz olarak belgelenmesine olanak sağlamıştır. Geleneksel yöntemlerle erişilemeyecek ya da belgelenmesi oldukça zahmetli olan bu bölümler, İHA ile güvenli, hızlı ve sistematik bir şekilde görüntülenmiştir.

Ayrıca İHA'lar, sabit kanatlı veya çok rotorlu (multikopter) yapılarına göre farklı avantajlar sunmaktadır. Özellikle çok rotorlu sistemler, düşük irtifada hassas manevralar yaparak karmaşık yapılara yakın uçuşlar gerçekleştirebilir. Bu da anıtsal yapılarda, mimari detayların daha fazla görüntülenmesine ve modelleme kalitesinin artmasına katkı sağlar (Karakaya & Ulvi, 2024).

İHA'ların fotogrametrik modelleme ile entegrasyonu, yalnızca görsel belgelenmeyle sınırlı kalmaz. Aynı zamanda bu modeller, ölçümsel (metrik) doğruluk da içerdiğinden; restorasyon planlaması, hasar analizi, yapı sağlığı izlemesi ve sanal gerçeklik (VR) uygulamaları gibi çok çeşitli alanlarda kullanılabilir hale gelmektedir. Bu çalışmada, Zafer Kapısı'nın hem görsel hem de metrik olarak doğru bir şekilde modellenmesi, ileride yapılacak müdahaleler için sayısal referans teşkil etmesi bakımından önem arz etmektedir.

Son olarak, İHA ile görüntüleme süreci çevresel koşullardan etkilenebilir. Rüzgâr, ışık kontrastı ve atmosferik şartlar, veri kalitesini doğrudan etkileyebilir. Bu çalışma özelinde, uygun hava koşulları altında planlanan uçuş sayesinde yüksek kaliteli görüntüler elde edilmiş, görüntü sayısı ve örtüşme oranı dikkatle seçilmiştir. Bu yaklaşım, modelin bütünlüğünü ve doğruluğunu artırmış; fotogrametrik iş akışının sağlıklı ilerlemesini mümkün kılmıştır.

1.5. Üç Boyutlu Modelleme Teknolojileri

Üç boyutlu modelleme teknolojileri, kültürel mirasın belgelenmesinde hem görselleştirme hem de ölçümsel doğruluk açısından yeni bir paradigma sunmaktadır. Özellikle fotogrametri (Structure from Motion – SfM) ve Lazer Taramaya (Light Detection and Ranging–LiDAR) dayalı teknikler, arkeolojik yapıların karmaşık geometrilerini detaylı biçimde yeniden oluşturma kapasitesine sahiptir. Bu teknolojiler sayesinde yapının yalnızca görsel özellikleri değil, aynı zamanda metrik bilgileri de yüksek doğrulukla dijital ortama aktarılabilmektedir (Remondino et al., 2006; Doneus et al., 2013).

Bu çalışmada, Zafer Kapısı'nın üç boyutlu modellenmesi amacıyla fotogrametri temelli bir iş akışı tercih edilmiştir. Bu yaklaşım, maliyet etkinliği, taşınabilirlik, çevresel etkiye duyarsızlık ve görsel–metrik bütünlüğü ile ön plana çıkmaktadır (Şenol et al., 2021). İHA ile çekilen yüzey görüntüleri, yüksek örtüşme oranı ve yeterli açısal çeşitlilik sayesinde fotogrametrik işleme uygun hale getirilmiş; yapı, nokta bulutu (point cloud), yüzey ağları (mesh) ve doku kaplamaları (texture mapping) ile detaylı biçimde yeniden modellenmiştir.

Çalışmada kullanılan yazılım, Agisoft Metashape Professional olup, SfM-MVS (Multi View Stereo) algoritmalarını destekleyen gelişmiş bir fotogrametrik modelleme paketidir. Bu yazılımın tercih edilme nedenleri arasında; kullanıcı dostu arayüzü, detaylı kalite ayarları, yer kontrol noktası (YKN) ve kontrol noktası (KKN) entegrasyon yeteneği ile çıktı doğruluk analizlerinin güvenilirliği bulunmaktadır. Metashape, özellikle kültürel miras yapılarına ilişkin çalışmalar için yaygın bir araç olarak önerilmekte ve literatürde birçok başarılı örnekle desteklenmektedir (Remondino et al., 2014; Özdemir, 2015).

Nokta bulutu üretiminde kullanılan parametreler –örneğin yoğunluk seviyesi, bağlanma eşiği, anahtar nokta limiti– model kalitesini doğrudan etkileyen unsurlardır. Bu çalışmada yüksek detayda nokta bulutu üretimi yapılmış, daha sonra bu bulut, üçgen ağına (mesh) dönüştürülerek yüzey modellemesi gerçekleştirilmiştir. Ardından, RGB görüntülerden elde edilen dokular modele kaplanmış ve yapı hem görsel hem de metrik olarak bütüncül bir dijital form kazanmıştır. Modelleme süreci boyunca kullanılan her adım, daha sonra gerçekleştirilecek restorasyon, simülasyon veya yapısal analiz çalışmalarına doğrudan katkı sağlayacak nitelikte yapılandırılmıştır.

Ancak fotogrametri temelli üç boyutlu modelleme, bazı sınırlamaları da beraberinde getirmektedir. Özellikle gölgelenmiş alanlar, bitki örtüsüyle kaplı yüzeyler veya homojen dokulu bölgeler (örneğin düz duvarlar) gibi unsurlar, fotogrametrik algoritmaların doğru eşleme yapmasını zorlaştırabilir. Bu çalışmada, böyle bölgeler için gerekirse ek görüntü çekimleri yapılarak boşluklar minimize edilmiş; yapı bütünlüğü korunmuştur.

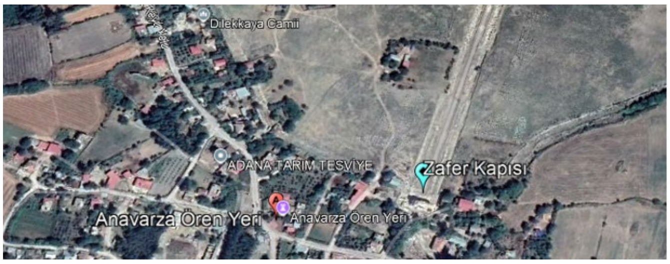
Sonuç olarak, kullanılan üç boyutlu modelleme teknolojileri, Anavarza Zafer Kapısı gibi yüksek, çok kemerli ve tarihi öneme sahip bir yapının hem görsel hem de analitik düzeyde belgelenmesini mümkün kılmıştır. Ortaya çıkan model, literatürde benzer çalışmalarla karşılaştırıldığında yüksek kalite, detay ve doğruluk düzeyiyle öne çıkmaktadır. Ayrıca bu model, yalnızca akademik araştırmalar için değil, aynı zamanda dijital arşivleme, restorasyon planlaması ve kültürel miras eğitimi gibi çok yönlü amaçlarla da kullanılabilir niteliktedir.

2. Yöntem

2.1. Çalışma Alanı

Anavarza Ören Yeri, Adana'nın Kozan ilçesi yakınlarında yer alan ve Roma, Bizans, Ermeni Krallığı ve İslam dönemlerine ait izler taşıyan önemli bir antik kenttir. Çalışmanın odak noktası olan Zafer Kapısı, kentin ana girişinde yer alan üç kemerli anıtsal bir yapıdır. Kapının mimari özellikleri, Roma dönemi mühendislik ve estetik anlayışını yansıtmaktadır.

Anavarza Ören Yeri, Zafer Kapısı Adana’nın Kozan İlçesinde 37°14′57.52″ Kuzey ve 35°53′50.25″E″ Doğu coğrafi koordinatlar ile deniz seviyesinden 34 m yükseklikte bulunmaktadır.



Şekil 1. Çalışma Alanı, Adana, Kozan, Anavarza Antik Kenti, Zafer Kapısı (Google Earth).

Anavarza, Çukurova bölgesinde yer almakta olup, geniş bir düzlüğe yayılmıştır. Romalıların, 3. yüzyılda Perslere karşı kazandığı zaferin anısına Roma İmparatorluğu’nun doğudaki ordugâh kenti olan Anavarza’ya zafer takı olarak inşa edilmiştir. Korint başlıklarla süslenmiş, sütunlu, pilasterli (dört köşeli sütun) nişlerin (İçerisine heykel konulan mihrap benzeri girinti) içlerinde heykel düzenlemeli, anıtsal ölçülerde bir yapıdır. Taşıdığı bu özellikler nedeniyle, Çukurova bölgesinde tek, Türkiye sınırları içerisinde ise birkaç anıtsal şehir kapısından biridir. Yapıdaki 2015 yılında başlayan restorasyon çalışmaları 2020 yılında tamamlanmıştır (URL 1).

Şekil 2. Zafer Kapısı restorasyon öncesi, Albert Gabriel (URL 1).

2.2. Veri Toplama

2.2.1. Kullanılan İHA Modeli ve Teknik Özellikler

Veri toplama sürecinde, yüksek çözünürlüklü görüntüler elde etmek için bir İnsansız Hava Aracı (İHA) kullanılmıştır. Kullanılan İHA' nın modeli DJI Matrice 300 RTK ve DJI Zenmuse P1 kamera ile donatılmıştır.

Şekil 4. İHA (üst) DJI Matrice 300 RTK (alt) DJI Zenmuse P1 kamera.

Dji modeli matrice 300 RTK, markanın modern havacılık uygulamalarından esinlenen en son nesil ticari İHA modelidir. İHA, 55 dakikaya kadar devam edebilen uçuş süresi ile kesintisiz çekim yapabilme şansına sahiptir Aynı zamanda geliştirilmiş Al nitelikleri, 6 yönlü algılama ve konumlandırma gibi daha pek çok özellikleri bünyesinde barındırmaktadır.

Matrice 300 RTK İHA, zekayı yüksek verim ve güvenirlik ile harmanlamaktadır. Böylece de çok yeni bir standart belirlemektedir. Dronun geliştirilmiş iletim sistemi OcuSync Enterpisei 15 kilometre uzaklığa kadar iletim olanağı sunmaktadır. Ayrıca üçlü kanal modu da yüksek çözünürlükte videoyu desteklemektedir (DJI, 2025).

İHA modeli 2,4 GHz ve 5,8 GHz arasında gerçek zamanlı bir otomatik geçiş sağlamaktadır. Bunun yanı sıra yüksek parazit içeren yerlerin yakın mesafesinden daha emniyetli uçuş olanağı sunarak AES-256 şifrelemesi ile emniyetli bir veri aktarımı olanağı da sağlamaktadır. Dji matrice 300 RTK İHA rafine gövde ve aktarım sistemi biçemi, zorlu şartlarda dahi daha verimli ve dengeli bir uçuş sağlamaktadır (DJI, 2025).

Dji matrice 300 RTK'yı görev ihtiyaçlarınıza uyum sağlayacak biçimde yapılandırılabilir. Cihaz 2,7 kilogram taşıma hacmi ile bir anda 3 taşıma hacmine kadar da monte edebilirsiniz. Bu cihaz ile görevler canlı olarak kaydedilebilir. İlerideki otomatik denetlemeler adına örnek vazife dosyaları meydana getirmek üzere dron hareketleri, gimbal yönlendirmeleri, fotoğraf çekimleri ve yakınlaştırma düzeyi gibi vazife hareketlerini de kaydedilebilir (URL 2). DJI Matrice 300 RTK İHA teknik özellikleri Tablo 1'de verilmektedir.

Tablo 1. DJI Matrice 300 RTK teknik özellikleri (DJI, 2025).

Özellik	Değer
Boyut	Katlanmamış, pervaneler hariç, 810 × 670 × 430 mm (U × G × Y) Katlanmış, pervaneler dahil, 430 × 420 × 430 mm (U × G × Y)
Ağırlık (aşağı doğru tekli gimbal ile)	Yaklaşık. 3,6 kg (pilsiz) Yaklaşık. 6,3 kg (iki TB60 pil ile)
Azami yük	2,7 kg
Çalışma Frekansı	2.4000-2.4835 GHz 5.725-5.850 GHz
Maksimum Açısal Hız	Genişlik: 300 ° / s, Sapma: 100 ° / s
Maksimum Çıkış Hızı	S modu: 6 m / s P modu : 5 m / s
Maksimum Rüzgar Direnci	15 m / s
Maksimum Uçuş Süresi	55 dk.
GNSS	GPS + GLONASS + Beidou + Galileo
Çalışma sıcaklığı	-20 ° C ila 50 ° C (-4 ° F ila 122 ° F)
Engel Algılama Aralığı	İleri / Geri / Sol / Sağ: 0.7-40m Yukarı / Aşağı: 0.6-30m
Batarya Enerji	274 Wh
Batarya Net ağırlık	Yaklaşık. 1,35 kg
Pil ömrü	Dahili pil: Yaklaşık. 2,5 saat Dahili pil + Harici pil: Yaklaşık. 4.5 saat
Giriş Koruma Sınıfı	IP45

Zenmuse P1 Kamera, 3 eksenli sabitlenmiş bir gimbal üzerinde değiştirilebilir sabit odaklı lenslerle tam çerçeve bir sensörü entegre eder. Fotogrametri uçuş görevleri için tasarlanan bu ürün, verimliliği ve doğruluğu tamamen yeni bir seviyeye taşır. P1, uçuş sırasında her 0,7 saniyede bir fotoğraf çekebilen ve tek bir uçuşta 3 km 2 mesafeyi kapsayabilen tam çerçeve, düşük gürültülü, yüksek hassasiyetli bir sensör içermekktedir. Küresel mekanik deklanşör ve modüller arası zamanı mikrosaniye seviyesinde senkronize eden yepyeni TimeSync 2.0 sistemiyle donatılan Zenmuse P1, gerçek zamanlı konum ve yönelim telafi teknolojisiyle birlikte kullanıcıların santimetre hassasiyetinde veri yakalamasını sağlıyor. 24/35/50mm lensler ve Akıllı Eğik çekim özelliği ile donatılabilen entegre 3 eksenli gimbal sayesinde 2B, 3B ve detaylı modeller yapılabilir (URL 3). DJI Zenmuse P1 Kamera Teknik Özellikleri Tablo 2 de verilmektedir.

Tablo 2. DJI Zenmuse P1 kamera teknik özellikleri (DJI, 2025)

Özellik	Değer
Boyut	198×166×129 mm
Ağırlık	Yaklaşık 800 gr
Güç	20W
IP Derecelendirmesi	IP4X
Desteklenen Uçak	Matris 300 RTK
Çalışma Sıcaklık Aralığı	-20° ila 50° C (-4° ila 122° F)
Mutlak Doğruluk	Yatay: 3 cm, Dikey: 5 cm
Sensör	Sensör boyutu (Sabit): 35,9×24 mm (Tam kare) Sensör boyutu (Maksimum video kayıt alanı): 34×19 mm Etkin Pikseller: 45MP Piksel boyutu: 4,4 μm
Diyafram Aralığı	f/2.8-f/16
Video Format	MP4,MOV
Video Çözünürlüğü	16:9 (1920×1080) 16:9 (3840×2160)

2.2.2. Uçuş Planlaması

Zafer Kapısı'nın üç boyutlu belgelenmesine yönelik veri toplama sürecinin başarısı, uçuş planlamasının özenli bir şekilde yapılmasına bağlıdır. Bu bağlamda, yapının mimari bütünlüğünü en yüksek düzeyde temsil edecek nitelikte bir veri seti elde edebilmek amacıyla hem yatay hem de eğimli açılardan görüntü alımına imkân veren çok yönlü bir uçuş stratejisi uygulanmıştır.

Fotogrametrik veri toplama işlemi öncesinde, yapının geometrisi, çevresel koşulları, aydınlatma durumu ve potansiyel engeller detaylı olarak incelenmiş; uçuş rotası bu ön değerlendirmeye göre optimize edilmiştir. Yapının üç cepheli mimarisini ve üst kotlardaki detayları etkili bir şekilde görüntüleyebilmek amacıyla dairesel (orbital) ve yanal (oblique) çekim stratejileri birleştirilmiştir. Bu kapsamda, yapı çevresinde sabit yarıçaplı bir uçuş rotası oluşturularak, hem yapı eksenine paralel (nadiral) hem de farklı eğim açılarında (oblique) görüntüler elde edilmiştir.

Uçuş yüksekliği, modelin çözünürlüğünü ve görüntülerin yer örnekleme mesafesini (YÖA) dengeleyecek şekilde 20 m ile 40 m arasında değişken yüksekliklerde planlanmıştır. Düşük irtifalar yapı yüzeyindeki ince detayların yakalanmasını sağlarken, daha yüksek irtifalar genel geometrik formun bütüncül şekilde belgelenmesine olanak tanımıştır. Kamera sistemi, yatay düzlemde 0° ile eğik açılarda (yaklaşık 45°) yapılandırılarak, dikey yüzeylerde veri eksikliği oluşmasının önüne geçilmiştir.

Uçuşlar, DJI Pilot yazılımı üzerinden önceden planlanarak otomatik modda gerçekleştirilmiş; uçuş sırasında hava koşulları sürekli izlenmiştir. Verinin kalite kaybına uğramaması için uçuşlar rüzgâr hızının 4 m/s'yi geçmediği, açık ve bulutsuz hava koşullarında, günün sabah saatlerinde gerçekleştirilmiştir. Bu sayede, homojen aydınlatma koşulları altında gölgelenme etkisi minimize edilmiş, ayrıca İHA stabilitesi ve görüntü keskinliği en üst düzeye çıkarılmıştır.

Planlanan uçuş görevi sırasında, GPS uydu sinyal kalitesi ve RTK düzeltmeleri sürekli takip edilmiş, modelleme için gereken fotogrametrik örtüşme koşulları sağlanmıştır. Bu bağlamda, boyuna örtüşme oranı %80, enine örtüşme oranı ise %70 olarak ayarlanmıştır. Bu oranlar, modelin yeniden yapılandırılmasında nokta eşleştirme kalitesini ve modelin geometrik doğruluğunu doğrudan etkileyen önemli parametrelerdir.

Uçuş planlamasında elde edilen görüntü setinin, hem metrik hem de estetik yönden yüksek kaliteli bir üç boyutlu model üretimine olanak tanıdığı görülmüştür. Özellikle yapının yüksek kotlarındaki taş işçiliği detayları ve kemer formundaki geçişler, farklı açılardan alınan görüntüler sayesinde eksiksiz bir şekilde yakalanmıştır.

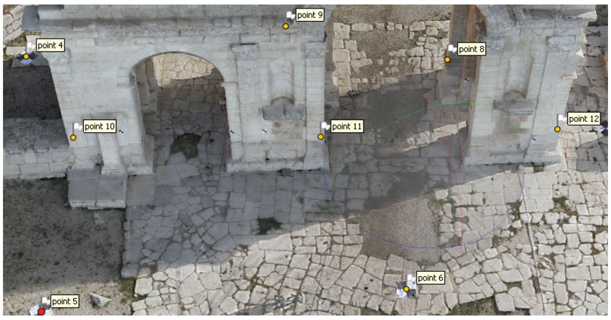
2.2.3. Görüntü Toplama Süreci

Fotogrametrik modellemenin temel girdisi olan görüntü verilerinin toplanması sürecinde, yapı yüzeyinin tüm geometrik ve mimari detaylarını içerecek şekilde kapsamlı bir çekim stratejisi uygulanmıştır. Çekimler, DJI Matrice 300 RTK İHA sistemi üzerine entegre edilmiş olan DJI Zenmuse P1 kamerası ile gerçekleştirilmiştir. Kamera, her 0.7 saniyede bir tetiklenen çekim modunda çalıştırılmış ve uçuş rotası boyunca görüntü kaybı yaşanmaması sağlanmıştır.

Yapının tüm cephelerinden ve üst kotlarından detaylı görsel veri sağlanabilmesi amacıyla hem yatay (nadiral) hem de eğik açılardan (yaklaşık 45°) yüksek çözünürlüklü görüntüler elde edilmiştir. Toplamda 114 adet JPEG formatında yüksek çözünürlüklü görüntü elde edilmiş; bu görüntüler, Exif meta verileri ile işlenmek üzere Agisoft Metashape yazılımına aktarılmıştır.

Modelin hem görsel hem de metrik doğruluğunu artırmak amacıyla, yapı çevresine toplam 12 adet yer kontrol noktası (YKN) yerleştirilmiştir. Bu noktalar, farklı yükseklik ve cepheleri temsil edecek şekilde yapının ön, arka ve yan kısımlarına dengeli biçimde dağıtılmıştır. Her bir GCP, GNSS-RTK alıcısı ile ±2 cm yatay ve ±3 cm düşey doğrulukla ölçülmüş; koordinatlar WGS84 (UTM Zone 37N) datumuna göre kaydedilmiştir.

YKN'lerin nokta tanımlamaları, yazılım ortamında manuel olarak işaretlenmiş ve tüm fotogrametrik hizalama işlemleri bu noktalara referanslanarak gerçekleştirilmiştir. Yer kontrol noktalarının yapıya göre konumsal dağılımı Şekil 5'te görsel olarak sunulmakta, her bir noktanın sayısal koordinat bilgileri ise Tablo 3'te detaylı biçimde verilmektedir.



Şekil 5. Bazı yer kontrol noktalarının üç boyutlu model üzerindeki dağılımı.

Tablo 3. Yer kontrol noktaları (WGS84 - UTM Zone 37N).

Nokta No	Y (doğu)	X (kuzey)	H (yükseklik, m)
2	35.898206	37.249235	62.164135
3	35.897020	37.249274	62.337643
4	35.897404	37.249227	62.173020
5	35.897431	37.249368	62.048171
6	35.897258	37.249407	62.297529
7	35.897060	37.249443	62.281471
8	35.897181	37.249303	63.730865
9	35.897265	37.249271	65.159657
10	35.897394	37.249305	64.818638
11	35.897272	37.249334	64.402764
12	35.897149	37.249363	64.459253

Tablo 3'teki noktaların konumsal doğrulukları, üç boyutlu modelin ölçeklenmesi ve hizalanmasında referans alınmış; özellikle metrik analizlerde kullanılacak modelin mutlak doğruluğu bu YKN'ler üzerinden güvence altına alınmıştır. Görsel olarak sunulan dağılım (Şekil 5), YKN'lerin yapı üzerinde homojen ve yapısal açıdan temsil kabiliyeti yüksek bir düzende yerleştirildiğini göstermektedir. Bu dağılım, nokta eşleştirme ve model çözümlemesi aşamalarında modelin sapmasız ve dengeli olarak oluşmasına katkı sağlamıştır.

2.3. Üç Boyutlu Modelleme

Bu çalışmada, Zafer Kapısı'nın dijital olarak belgelenmesi amacıyla, fotogrametri temelli üç boyutlu modelleme yöntemi uygulanmıştır. Yöntemin temelini, Görüntülerden Yapılandırma (Structure from Motion – SfM) algoritmasına dayalı sayısal model üretimi oluşturmaktadır. SfM, örtüşen iki boyutlu görüntülerdeki ortak ilgi noktalarını tespit ederek kamera pozisyonlarını ve nesne geometrisini eşzamanlı olarak yeniden yapılandırma esasına dayanır. Bu süreç, karmaşık mimari yapıların yüksek doğrulukta ve fotogerçekçi biçimde dijital ortama aktarılmasına olanak tanır.

Modelleme süreci, Agisoft Metashape Professional (v2.0.3) yazılımı kullanılarak yürütülmüştür. Yazılım, YKN ile referanslandırılan yüksek çözünürlüklü görüntülerden otomatik olarak nokta bulutu üretimi, 3B yüzey modeli (örgü) oluşturulması ve doku kaplama işlemlerini gerçekleştirmektedir. Tüm modelleme süreci, aşağıda açıklanan sıralı işlem adımları doğrultusunda gerçekleştirilmiştir:

İlk olarak, toplam 114 adet yüksek çözünürlüklü JPEG formatındaki görüntü, yazılım arayüzüne yüklenmiştir. Görüntülere ait içsel kamera parametreleri (odak uzaklığı, sensör boyutu, vb.) EXIF verileri aracılığıyla yazılım tarafından otomatik olarak algılanmıştır. Görüntülerin kalite kontrolü manuel olarak yapılmış, bulanıklık, aşırı pozlama veya örtüşme eksikliği olan karelere rastlanmamıştır.

SfM algoritması ile gerçekleştirilen fotoğraf hizalama (kamera yöneltmesi) aşamasında, yazılım her bir görüntü için konum ve yönelim parametrelerini hesaplamış ve bu sayede kaba bir seyrek nokta bulutu elde edilmiştir. Bu adımda kullanılan temel parametreler; hizalama doğruluğu "Yüksek", ana nokta sınırlaması 40.000, destek nokta sınırlaması 4.000 ve örtüşme tipi "ileri + yanal" olarak belirlenmiştir.

Bunu takiben, sahada ölçülen 12 adet YKN, yazılım ortamında görüntüler üzerinde manuel olarak işaretlenmiş ve koordinat dosyası yüklenerek sistem mutlak koordinatlara referanslandırılmıştır. Yapılan bundle adjustment (demet dengeleme) işleminden sonra model optimize edilmiştir.

Hizalama işlemi sonrasında, yoğun nokta bulutu oluşturma adımına geçilmiştir. Bu adımda yapı yüzeyine ait daha detaylı geometrik bilgi elde edilmiştir. Kullanılan ayarlar: nokta yoğunluğu "Yüksek", derinlik filtreleme "Orta", ve tüm görüntü alanını kapsayacak şekilde maskeleme yapılmadan uygulanmıştır.

Yoğun nokta bulutundan elde edilen verilerle, 3B yüzey modeli (örgü) oluşturulmuştur. Bu adımda, "derinlik haritası tabanlı" yeniden yapılandırma yöntemi tercih edilmiş; yüzey tipi olarak "arbitrary surface" seçilmiştir. Oluşturulan ağ modeli yaklaşık 1 milyon üçgen yüzey içermekte olup, karmaşık mimari öğeleri yeterli detayda temsil etmektedir.

Son adımda, oluşturulan 3B örgü modeli üzerine doku kaplama (texture mapping) işlemi uygulanmıştır. Gerçekçi görsellik sağlamak amacıyla, "mozaik" tipi doku haritalama yöntemi tercih edilmiştir. Harita boyutu 8192 × 8192 piksel olarak belirlenmiş ve tek bir doku haritası kullanılmıştır. Kaplama işlemi sırasında tüm görüntü seti kullanılmıştır.

Modelleme sürecinin sonunda, 3B model hem görsel hem de metrik analizler için .OBJ ve .LAS formatlarında dışa aktarılmıştır. Hazırlanan model; yapının mimari detaylarını, hasar durumlarını ve yüzey karakteristiklerini yüksek doğrulukla yansıtmakta, restorasyon ve dijital koruma çalışmalarına uygun bir veri temeli sunmaktadır. Model doğruluğuna ilişkin nicel değerlendirmeler, 2.4. Model Doğruluk Analizi başlığı altında ayrıntılı olarak sunulmuştur.

2.4. Model Doğruluk Analizi

Üç boyutlu modelleme sürecinde elde edilen dijital çıktının geometrik doğruluğunun değerlendirilmesi, çalışmanın güvenilirliğini ve bilimsel geçerliliğini artıran önemli bir adımdır. Bu doğrultuda, Zafer Kapısı'nın dijital modelinin metrik doğruluğu, YKN ve kontrol noktaları (KN) kullanılarak analiz edilmiştir. Modelleme süreci Agisoft Metashape yazılımı üzerinden yürütülmüş ve yazılımın sağladığı hata raporları temel alınarak değerlendirmeler yapılmıştır.

Toplamda 12 adet yer kontrol noktası sahaya yerleştirilmiş; bunlardan 6'sı modelin ölçeklenmesi ve hizalanması amacıyla YKN olarak, 6'sı ise doğrulama amacıyla KN olarak kullanılmıştır. Bu noktaların tümü, GNSS destekli RTK yöntemiyle ±2 cm konumsal hassasiyetle ölçülmüş ve WGS84 (UTM Zone 37N) datumuna göre koordinatlandırılmıştır.

Agisoft Metashape yazılımında yapılan demet dengeleme işlemi sonucunda, modelin içsel ve dışsal yönelimi tamamlanmış ve YKN'ler yardımıyla mutlak koordinatlara referanslandırılmıştır.

3. Bulgular

3.1. Zafer Kapısı'nın Üç Boyutlu Modeli

İHA fotogrametrisi ile üretilen üç boyutlu model, Zafer Kapısı'nın mevcut yapısal durumu ve mimari detaylarını dijital ortamda başarılı biçimde temsil etmiştir. Modelleme süreci sonunda oluşturulan yüzey modeli, gerek geometrik bütünlük gerekse görsel doğruluk açısından arkeolojik belgelenme standartlarını karşılamaktadır. 3B modelin çeşitli görselleri Şekil 6'da verilmiştir.

Model üzerinde yapılan incelemelerde, Zafer Kapısı'nın üç kemerli anıtsal yapısı, cephe düzenlemeleri, üst kotlardaki taş silmeler ve niş boşlukları net şekilde izlenebilmiştir. Özellikle kemerlerin tonoz yapıları, sütun kaideleri, taş blokların derz çizgileri ve üst örtü yüzeyindeki düzensiz taş dokuları modelde detaylı biçimde görünür durumdadır. Yapıya özgü mimari oranlar, yükseklik farkları ve açıklık-derinlik ilişkileri fotogerçekçi bir şekilde modellenmiştir.

Model üretimi sırasında bazı zorluklarla da karşılaşılmıştır. Özellikle kapının alt kotlarında yer alan gölgelenmeler ve taş döşemeler üzerindeki reflektif alanlar, görüntülerin eşleştirilmesinde sınırlı düzeyde hata üretmiştir. Ayrıca, kuzey cephesinde yapı çevresinde yer alan çevresel kalıntılar ve düzensiz yüzey eğimleri, nokta yoğunluğunun homojen dağılmasını kısmen engellemiştir. Buna karşın, yüksek çözünürlüklü görüntülerin çok açılı çekimi ve homojen YKN dağılımı sayesinde model bütünlüğü korunmuş ve eksik alan oluşumu büyük oranda engellenmiştir.

Modelin genel formuna ait örnek görseller Şekil 6'da sunulmaktadır. Bu görseller, kapının ön ve arka cephelerine ait 3B yeniden yapılandırılmış görünüşlerini içermekte olup, taş işçiliği detaylarının ve genel mimari karakterin modelde ne ölçüde yansıtıldığını ortaya koymaktadır.

(a)

(b)

Şekil 6. 3B modelin çeşitli görselleri (a, b).

3.2. Doğruluk Değerlendirmesi

Üç boyutlu modelin metrik doğruluğunun değerlendirilmesi, modelin arkeolojik belgelenme, belgeleme sonrası analiz ve restorasyon planlaması gibi uygulamalarda güvenle kullanılabilmesi açısından kritik öneme sahiptir. Bu doğrultuda, model doğruluğu hem yöneltme aşamasında kullanılan YKN hem de modellemede kullanılmayan ancak doğrulama amacıyla ölçülmüş kontrol noktaları KN üzerinden değerlendirilmiştir. Çalışma sahasında toplam 12 adet kontrol noktası belirlenmiş; bunlardan 6'sı YKN olarak kullanılarak modelin ölçeklendirilmesi ve yöneltilmesi gerçekleştirilmiş, geri kalan 6'sı ise KN olarak yalnızca doğrulama amacıyla değerlendirmeye alınmıştır. Tüm noktalar GNSS destekli RTK yöntemiyle ±2 cm yatay, ±3 cm düşey doğrulukla ölçülmüş ve WGS84 (UTM Zone 37N) koordinat sistemine göre tanımlanmıştır.

Agisoft Metashape yazılımında yapılan demet dengeleme işlemi sonrasında model, gerçek dünya koordinat sistemine entegre edilmiş ve modelleme süreci tamamlanmıştır. Yazılım tarafından sağlanan hata raporlarına göre, hem YKN'ler hem de KN'ler üzerinden konumsal hata analizleri yapılmıştır. Sonuçlar, ortalama mutlak hata (Mean Error) ve kök ortalama kare hata (Root Mean Square Error – RMSE) biçiminde değerlendirilmiştir. Sonuçlar Tablo 4'te verilmiştir.

Tablo 4. Doğruluk değerlendirmesi.

Nokta Türü	Koordinat Bileşeni	Ortalama Hata (m)	RMSE (m)
YKN	Y (Doğu)	0.014	0.021
	X (Kuzey)	0.018	0.025
	Z (Yükseklik)	0.023	0.031
KN	Y (Doğu)	0.019	0.028
	X (Kuzey)	0.021	0.030
	Z (Yükseklik)	0.032	0.044

Elde edilen sonuçlara göre, yöneltmede kullanılan YKN'lerde ortalama yatay hata yaklaşık **±2.5 cm**, düşey hata ise **±3.1 cm** düzeyinde hesaplanmıştır. Doğrulama amacıyla kullanılan KN'lerde ise yatayda **±3.0 cm**, düşeyde ise **±4.4 cm** seviyesinde hata gözlenmiştir. Bu değerler, modelin yüksek doğrulukla üretildiğini ve hem görsel hem de metrik analizlerde güvenle kullanılabileceğini göstermektedir. Özellikle arkeolojik yapılar gibi ölçüsel duyarlılığın önemli olduğu belgelenme çalışmalarında, bu düzeydeki RMS hata oranları, literatürde kabul gören sınırlar içerisinde yer almaktadır (Remondino & El-Hakim, 2006; Yiğit & Uysal, 2025). Elde edilen doğruluk seviyesi, restorasyon planlaması, hasar analizi ve dijital arşivleme gibi ileri uygulamalarda modelin etkin şekilde kullanılabileceğini göstermektedir.

3.3. İHA ile Belgelenmenin Avantajları, dezavantajları

Bu çalışmada, İHA'lar kullanılarak gerçekleştirilen belgelenme süreci, geleneksel yöntemlere kıyasla birçok avantaj sağlamıştır. İHA'lar, Zafer Kapısı'nın tüm detaylarını kısa bir süre içinde belgelemeyi başarmıştır. Geleneksel yöntemlerle günler sürebilecek bir süreç, birkaç saat içinde tamamlanmıştır. Kapının yüksek ve erişilmesi zor kısımları, İHA'lar sayesinde kolayca belgelenmiştir. Bu, özellikle kemerlerin üst kısımlarındaki detayların incelenmesini mümkün kılmıştır.

İHA'lar ve fotogrametri yazılımları, lazer tarama gibi daha pahalı teknolojilere kıyasla daha düşük maliyetle yüksek doğrulukta sonuçlar sunmuştur. Üç boyutlu model, kapının mimari detaylarını ve yüzey özelliklerini yüksek çözünürlükte yansıtmıştır. Bu hem görsel hem de teknik analizler için önemli bir avantaj sağlamıştır.

İHA'lar ile yürütülen çalışmalarda, geleneksek yöntemlerle karşılaştırması Tablo 5'te görülmektedir.

Tablo 5. Yöntemlerin karşılaştırması.

Ölçüt	İHA ile belgeleme	Geleneksel yöntemler
Süre	3-4 saat	Günler
Maliyet	Düşük	Yüksek
Erişim	Kolay	Zor
Detay Seviyesi	Yüksek	Orta

Modelleme sürecinde bazı zorluklarla karşılaşılmış ve bu zorluklar çalışmanın sınırlamalarını oluşturmuştur. Veri toplama süreci sırasında rüzgâr ve ışık koşulları, İHA'nın stabilitesini ve görüntü kalitesini etkileyebilmiştir. Bu nedenle, uçuş planlaması sırasında hava koşullarına dikkat edilmesi gerekmiştir. Çekilen yüzlerce fotoğrafın işlenmesi ve üç boyutlu modelin oluşturulması, yüksek işlem gücü gerektirmiştir. Bu süreç, özellikle yoğun nokta bulutu ve doku kaplama aşamalarında zaman alıcı olmuştur. Kapının bazı kısımlarında, bitki örtüsü veya gölgeler nedeniyle eksik veriler oluşmuştur. Bu durum, modelin bazı bölgelerinde detay kaybına neden olmuştur. Fotogrametri yazılımlarının bazı sınırlamaları, özellikle karmaşık geometrilere sahip bölgelerde modelin doğruluğunu etkileyebilmiştir.

Zafer Kapısı'nın üç boyutlu modeli, restorasyon ve koruma çalışmalarına önemli bir katkı sağlamaktadır. Model, kapının mevcut durumunu detaylı bir şekilde belgeleyerek, restorasyon planlaması için bir temel oluşturmuştur. Üç boyutlu model, kapının dijital ortamda korunmasını sağlamış ve gelecekteki çalışmalar için bir referans noktası oluşturmuştur. Model, restorasyon müdahalelerinin dijital ortamda simüle edilmesine olanak tanımaktadır. Bu, restorasyon sürecinde daha bilinçli kararlar alınmasını sağlayabilir.

4. Tartışma

Bu çalışmada, İHA ve üç boyutlu modelleme teknolojileri kullanılarak Anavarza Zafer Kapısı'nın dijital olarak belgelenmesi gerçekleştirilmiştir. Literatürde İHA tabanlı fotogrametri yönteminin arkeolojik alanlarda yaygın olarak kullanıldığı bilinmektedir (Campana, 2017; Verhoeven, 2011). Ancak bu çalışma, özellikle anıtsal bir giriş kapısının yüksek çözünürlüklü olarak belgelenmesi bakımından literatüre yenilikçi ve özgün bir katkı sunmaktadır.

Geleneksel belgelenme yöntemlerinin (örneğin çizim, fotoğraf, elle ölçüm) zaman alıcı ve sınırlı çözünürlükte veri sunduğu bilinmektedir. Lazer tarayıcı sistemleri ise yüksek doğruluk sağlamasına rağmen, donanım maliyeti ve operasyonel karmaşıklık açısından her projede uygulanabilir değildir. Bu bağlamda, İHA fotogrametrisi ile yalnızca birkaç saat içinde hem görsel hem de metrik doğruluğu yüksek bir model üretilebilmiş ve yapı tüm mimari detaylarıyla belgelenmiştir. Elde edilen model, Zafer Kapısı'nın kemer yapıları, taş işçiliği ve üst kot detaylarını fotogerçekçi bir biçimde ortaya koymuş; özellikle insan erişiminin zor olduğu alanlar İHA'lar sayesinde başarıyla belgelenebilmiştir.

Modelin sağladığı dijital çıktı, yalnızca arşivleme amacıyla değil; aynı zamanda restorasyon planlaması, konservasyon müdahaleleri, yapısal analizler ve sanal sergileme gibi ileri uygulamalar için de uygun niteliktedir. Sayısal doğruluğu literatürle uyumlu düzeyde olan model, gelecekte yapılacak müdahalelerin planlanmasında karşılaştırmalı analizlere olanak tanımaktadır. Bu yönüyle çalışma, dijital kültürel mirasın belgelenmesi ve korunması sürecine katkı sağlayan disiplinlerarası bir yaklaşım ortaya koymaktadır.

Bununla birlikte, İHA fotogrametrisinin bazı sınırlılıkları da göz önünde bulundurulmalıdır. Özellikle veri toplama süreci, rüzgâr, ışık yönü, hava durumu gibi dış çevre koşullarından doğrudan etkilenmektedir. Bu çalışmada uçuşlar elverişli meteorolojik koşullarda planlanmış olsa da farklı dönemlerde benzer verimliliğin elde edilmesi her zaman mümkün olmayabilir. Ayrıca, yoğun nokta bulutu üretimi ve doku kaplama işlemleri, yüksek işlem gücü ve zaman gerektirmiştir. Özellikle taş döşemeler üzerindeki parlama, gölgelenme ve bitki örtüsü gibi faktörler, bazı bölgelerde veri kaybına neden olmuş; karmaşık geometrilere sahip alanlarda modelin lokal doğruluğu azalmıştır.

Fotogrametri yazılımlarının algoritmik sınırlamaları, yüzey topolojisinin net şekilde algılanmasında ve doku kalitesinin homojen dağılımında etkili olabilmektedir. Bu tür durumlar, özellikle hasar analizi ve detay ölçekli uygulamalar için modelin sınırlı yorumlanmasına neden olabilir.

Sonuç olarak, bu çalışma İHA tabanlı 3B modellemenin kültürel mirasın belgelenmesi ve korunmasında sunduğu avantajları açıkça ortaya koymuştur. Disiplinlerarası bir yaklaşımla yürütülen dijital belgelenme süreçlerinin, kültürel mirasın hem bilimsel hem de toplumsal düzeyde daha geniş kitlelere ulaştırılmasına katkı sağlayacağı değerlendirilmektedir.

5. Sonuçlar ve Öneriler

Bu çalışmada, Adana ili Kozan ilçesinde yer alan Anavarza Ören Yeri'ndeki Zafer Kapısı'nın belgelenmesi amacıyla, İHA ve üç boyutlu fotogrametri yöntemleri kullanılmıştır. Geleneksel belgeleme tekniklerine kıyasla daha hızlı, düşük maliyetli ve yüksek doğruluk sağlayan bu yöntem sayesinde, yapının mimari detayları fotogerçekçi ve metrik hassasiyetle dijital ortama aktarılmıştır.

Modelleme süreci sonucunda elde edilen 3B model, kemer yapıları, taş işçiliği ve üst kot detaylarını ayrıntılı biçimde temsil etmiş; yapının mevcut durumu, restorasyon planlaması ve arşivleme amaçları için sayısal olarak belgelenmiştir. Model hem görsel hem de konumsal doğruluk açısından kabul edilebilir sınırların altında hata oranlarıyla değerlendirilmiş ve saha ölçümleri ile uyumlu bulunmuştur.

5.1. Çalışmanın Katkısı

Bu çalışma, İHA fotogrametrisi ile mimari olarak karmaşık bir anıtsal yapının kısa sürede ve yüksek hassasiyetle modellenebileceğini göstermiştir. Ayrıca dijital modellerin, kültürel mirasın korunması, belgelenmesi, sanal ortamlarda sergilenmesi ve eğitim süreçlerinde kullanılmasına yönelik potansiyelini ortaya koymuştur. Zafer Kapısı'nın üç boyutlu modellemesi ile elde edilen çıktılar, restorasyon senaryolarının dijital ortamda test edilmesine ve müdahale kararlarının daha bilinçli alınmasına olanak tanımaktadır.

5.2. Öneriler

Gelecekte benzer çalışmalarda doğruluğun artırılması ve süreçlerin iyileştirilmesi amacıyla aşağıdaki öneriler sunulmaktadır:

- Lidar entegrasyonu: Yoğun bitki örtüsü ya da karmaşık geometrilere sahip yapılar için İHA fotogrametrisi ile Lidar teknolojisinin birleştirilmesi önerilir. Bu, hem yüzey hem de derinlik verisinin hassas biçimde elde edilmesini sağlar.
- Yapay zekâ destekli yazılımlar: Veri işleme süresini kısaltmak ve eksik alanları tamamlamak amacıyla yapay zekâ tabanlı algoritmalar kullanılabilir.
- Yüksek çözünürlüklü kameralar: İHA'lara entegre edilen sensörlerin çözünürlükleri artırılarak, küçük ölçekli mimari detaylar daha net şekilde belgelenebilir.
- Dijital sergileme ve gerçeklik ve artırılmış gerçeklik entegrasyonu: Üretilen üç boyutlu modeller sanal gerçeklik ve artırılmış gerçeklik platformlarında sunularak, halkın kültürel mirasa erişimi ve ilgisi artırılabilir. Özellikle genç nesillerin katılımı için dijital turlar ve etkileşimli sergiler önerilmektedir.
- Eğitim ve kapasite geliştirme: Arkeologlar, mimarlar ve mühendisler için İHA tabanlı belgeleme ve üç boyutlu modelleme üzerine saha ve yazılım temelli eğitim programları düzenlenmelidir.
- Fon kaynaklarının etkin kullanımı: Ulusal ve uluslararası destek programları (örneğin TÜBİTAK, UNESCO, EU Horizon) ile bu tür belgelenme projeleri fonlanabilir; kamu–akademi–yerel yönetim iş birlikleri ile sürdürülebilirlik sağlanabilir.
- Hibrit yöntemlerin teşvik edilmesi: İHA fotogrametrisi, lazer tarama ve klasik ölçüm tekniklerinin entegre kullanımı ile daha kapsamlı ve doğruluğu yüksek belgelenme projeleri yürütülebilir.

Sonuç olarak, bu çalışma dijital belgeleme teknolojilerinin kültürel miras alanında sunduğu olanakları göstermekte ve İHA tabanlı üç boyutlu modellemenin, arkeolojik yapıların korunması ve gelecek nesillere aktarılmasında etkin bir araç olduğunu ortaya koymaktadır.

Yazarların Katkısı

Birinci yazar: Çalışma tek yazarlıdır ve tüm katkı birinci yazara aittir.

Çıkar Çatışması Beyanı

Yazarlar arasında herhangi bir çıkar çatışması bulunmamaktadır.

Araştırma ve Yayın Etiği Beyanı

Yapılan çalışmada araştırma ve yayın etiğine uyulmuştur

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A Systematic Literature Analysis of the Public Perception of UAVs

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Abstract

This study aims to conduct a systematic literature review of the public perception of unmanned aerial vehicles (UAVs) used in various fields. The research seeks to understand public attitudes toward UAVs and the underlying reasons for these attitudes. The study did a detailed search using specific keywords in the Scopus and Google Scholar databases. The search strings used for database queries were determined, and exclusion criteria for article screening were established. Records were identified through database searches, and duplicates were removed following the PRISMA flow diagram. Articles were re-evaluated for eligibility, and the studies included in the synthesis were identified. The study yielded important findings for understanding the societal impact of UAV technology and its future trajectory. Various factors affect the public perception of UAVs, and the consequences of this perception are directly related to how individuals and societies adopt the technology. In this respect, it is evident that stakeholders should consider public perceptions when making decisions regarding UAV usage. Given that privacy concerns surrounding UAVs may lead to public debate, managing risks and developing communication strategies with the public may also be beneficial.

Keywords: Privacy, unmanned aerial vehicles, public perception, risk management, societal acceptance,

Toplumun İHA'lara Karşı Algısının Sistematik Literatür Analizi

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Özet

Bu çalışmanın amacı, çeşitli alanlarda kullanılan İnsansız Hava Araçları (İHA) hakkındaki toplumsal algıya ilişkin sistematik bir literatür taraması yapmaktır. Araştırma, İHA'lara yönelik toplumsal tutumları ve bu tutumların altında yatan nedenleri anlamaya çalışmaktadır. Çalışma kapsamında, Scopus ve Google Akademik veri tabanlarında belirli anahtar kelimeler kullanılarak ayrıntılı bir arama yapılmıştır. Veritabanı sorguları için kullanılan arama dizeleri belirlenmiş ve yayın taraması için dışlama kriterleri oluşturulmuştur. Kayıtlar veritabanı aramaları yoluyla belirlenmiş ve PRISMA akış şeması izlenerek tekrarlar kaldırılmıştır. Yayınlar uygunluk açısından yeniden değerlendirilmiş ve senteze dahil edilen çalışmalar belirlenmiştir. Çalışma, İHA teknolojisinin toplumsal etkisini ve gelecekteki yörüngesini anlamak için önemli bulgular ortaya koymuştur. İHA'lara ilişkin toplumsal algı çeşitli faktörlerden etkilenmektedir ve bu algının sonuçları, bireylerin ve toplumların teknolojiyi nasıl benimsediğiyle doğrudan ilişkilidir. Bu bağlamda, paydaşların İHA kullanımına ilişkin kararlar alırken toplumsal algıları dikkate almaları gerektiği açıktır. İHA'lara ilişkin mahremiyet endişelerinin kamuoyunda tartışmalara yol açabileceği göz önüne alındığında, risklerin yönetilmesi ve toplumla iletişim stratejilerinin geliştirilmesi de faydalı olabilir.

Anahtar Kelimeler: Gizlilik, İnsansız hava araçları, kamu algısı, risk yönetimi, sosyal kabul.

1. Introduction

Unmanned Aerial Vehicles (UAVs) represent aircraft that do not have a crew or passengers inside, have technically diverse equipment such as cameras, fertilizer nozzles, lidar, sensors etc. can be remotely controlled, or have the ability to fly autonomously. UAVs exhibit significant variations in terms of size, range, weight, engine type, and performance to accommodate various payloads, including communication devices, navigation equipment, sensors, and cameras. (Elmeseiry et al., 2021; Mohsan et al., 2022, 2023).

UAVs have started to be used in commercial and private areas, especially with technological advancements in recent years. Furthermore, this developing technology has also caused an increase in the areas of use of UAVs. UAVs are utilized in agricultural activities, aerial imaging, cargo transportation, and search and rescue activities. For example, considering search and rescue activities, it can be said that not only activities aimed at finding are carried out, but also the number of people at risk during a disaster is conveyed, and actions are taken accordingly (Mohamed et al., 2020).

UAVs also significantly affect public acceptance. Various factors influence the perception that society develops toward UAVs, and the consequences of this attitude are closely related to how individuals and societies adopt the technology (Sabino et al., 2022).

Studies in the literature examine the perception of UAVs in numerous dimensions, such as safety concerns, privacy, ease of access, societal acceptance, and technological innovation. These studies explain essential results for understanding the public attitudes toward UAVs and the reasons for these attitudes. Nevertheless, the available literature on the effects of UAVs on society and how these effects are perceived is still not at the desired level. Therefore, the analysis of the current literature is one step ahead to systematically examine the public perception of UAVs (Wang et al., 2023).

The present study aims to be pioneering for future research on the societal acceptance of UAVs and to guide researchers and decision-makers on the use of UAVs by indicating the factors affecting the benefits and risks perceived by society. This study aims to present the results in a clear and reproducible way through literature analysis. In this respect, it is aimed to inform researchers, carry thoughts about the dominant perspectives and attitudes to the upper level, and contribute by expressing the possible knowledge gaps in the literature on the societal acceptance of the comprehensively advancing technology.

This study aims to systematically analyze the existing literature on public perception of Unmanned Aerial Vehicles (UAVs), focusing particularly on societal acceptance, privacy concerns, attitudes, and related regulatory and operational dimensions. The novelty of this research lies in its comprehensive approach to classifying and synthesizing recent studies using the PRISMA 2020 methodology, which ensures transparency and replicability. Unlike prior fragmented reviews, this study consolidates diverse perspectives and highlights existing research gaps, offering a clearer roadmap for future academic work and policymaking.

The paper is structured as follows: Following the introduction, Section 1 presents the research methodology, including the selection process and inclusion/exclusion criteria. Section 2 provides the results of the literature review, highlighting key statistics and trends in publication. Section 3 discusses the thematic clusters related to public perception, such as regulatory, operational, external, and economic factors. Finally, Section 4 presents the conclusions and implications for researchers, practitioners, and policymakers.

2. Method

The current study, which addresses research on a systematic literature analysis of the public perception of UAVs, employed the meta-analysis method, one of the systematic review approaches. A meta-analysis statistically combines many independent studies and findings regarding the determined subject or research question. It aims to yield reliable results by systematically analyzing the data from various studies (Göktaş, 2018).

The PRISMA 2020 (The Preferred Reporting Items for Systematic Reviews and Meta-Analyses) used in meta-analysis studies was adopted in the research process. PRISMA 2020 represents the guide used to ensure the transparency of meta-analysis studies and to report findings in a standard manner. According to the said guide, the research questions and subjects are clearly defined. Then, records are determined using the PRISMA flow chart, which involves the process of determining, selecting, and including articles with reviews. In the present study, the data selection and search strategy and the inclusion and exclusion criteria were established with the PRISMA model (Pençe, 2024).

2.1. Research Question and Research Terms

Within the scope of the above-mentioned method, the main research question in our literature review was determined as follows:

''What is known about the societal acceptance factors regarding the public perception of UAVs?''

The four basic concepts related to our main research question specified in Table 1. are UVAs, Societal Acceptance, Attitude, and Privacy. These research concepts alone or UAV 'AND' Societal Acceptance 'AND' Attitude 'AND' Privacy were identified as the search concepts. The concepts of Equipment 'AND' military 'AND' security 'AND' power 'AND' resolution specified in Table 2. were the strings excluded when searching with these research concepts in literature.

Table 1. Search strings included in the study.

Search Option	Search String
All Fields (Anywhere in the article)	*UAV and *public perception and *attitude and * privacy

Studies on civilian areas of use of UAVs were addressed to concretize the public perception of UAVs and make them more understandable. In this regard, studies on military use were excluded with concepts indicated in Table 2. Additionally, technical studies in this field were excluded to reach studies on the public perception of UAVs, the subject of the current work, more clearly. Thus, studies on UAVs' communication or UAV equipment and similar studies were excluded from the review's scope.

Table 2. Search strings excluded from the study.

Search Option	Search String Excluded
All Fields (Anywhere in the article)	*equipment and *military and *security and *power and *resolution

Table 3. specifies the exclusion criteria for the literature review within certain concepts from A to H. Information is provided about the results that can be considered negative when evaluated in terms of eligibility for our research subject, even if the search is done with these central concepts.

Table 3. Exclusion criteria for the literature review.

Central Concept	Exclusion Criteria
Unmanned Aerial Vehicles	**A**. Information on UAVs is included but is outside the scope of the article. For example, subjects related to technical information (development of the UAV test setup, etc.).
	B. The article generally includes technological perceptions but does not directly address UAVs.
Societal Acceptance	**C.** Although the concept of societal acceptance is included in different sections of the article, it is not discussed in detail.
Attitude	**D**. Although the themes of societal acceptance with regard to the technology are addressed, UAVs are not examined in a special section.
Privacy	**E.** Not the attitude toward the use of UAVs but the attitude observed when purchasing UAVs is addressed.
Technical Criteria	**F.** Privacy issues are indicated when manufacturing UAVs. Privacy regarding images is not discussed.
	G. Full text is unavailable for high-level evaluation.
	H. The article is not in English.

2.2. Selection of Articles

Articles published in English between 2015 and 2024 in the academic search engine Google Scholar (*Google Scholar*, 2024) and the academic database Scopus (*Scopus*, 2024) were included in the literature review. The articles obtained at the first stage were compiled by conducting a similarity scan. Among the remaining articles, those eligible for our subject were selected, and similar ones were removed again. After three rounds, 55 articles were evaluated according to their eligibility. Duplicates, studies not eligible for the research subject, those not in English, and those in abstract form (full text unavailable) were excluded.

As seen in Figure 1, there are many duplicates based on the PRISMA flowchart (Prizma, 2024) applied as a research method in the study. When reviewing the studies, duplicates were excluded. Afterward, studies directly integrated with the subject were selected. After excluding similar articles and examining the publications in terms of their eligibility for the subject, the results regarding 55 articles were reported in the current study.

Additionally, in searches through Google Scholar and Scopus, although the search is done with the inclusion and exclusion criteria in Google Scholar, articles not displaying integrity with the subject are frequently encountered. Accordingly, more studies that could be examined regarding eligibility for the subject were found when we applied the inclusion and exclusion criteria in searches through Scopus.

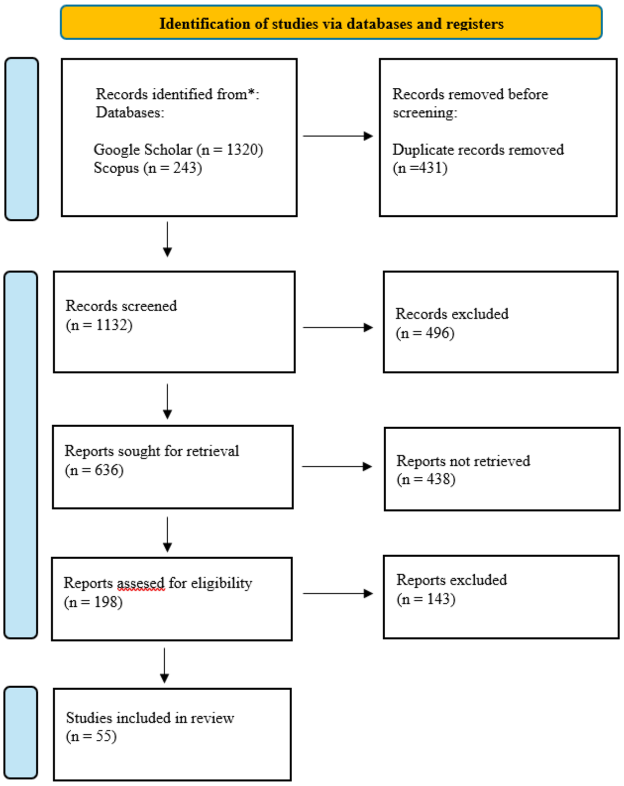

Figure 1. PRISMA flowchart.

3. Results

Considering the distribution of the articles reviewed by years, most studies were conducted in 2024 (Table 4). Against the 15 articles published in 2024, there is one study in 2015 and one study in 2017.

Figure 2. shows the count of articles according to the study's geographic location on the world map. Among the 55 studies included in the review, a maximum of 20 and a minimum of 1 study were published in different countries. The highest number of studies was conducted in the United States with 20 articles, followed by Germany with 7 articles, China with 5 articles, India with 4 articles, and Malaysia with 4 articles.

Table 5. contains the list of journals where the 55 articles included in the review were published. The table shows that most articles were published in the journal "Technology in Society."

Table 4. Distribution of selected articles by years.

Year When the Article Was Published	Count of Articles
2015	1
2016	2
2017	1
2018	2
2019	2
2020	4
2021	7
2022	14
2023	7
2024	15

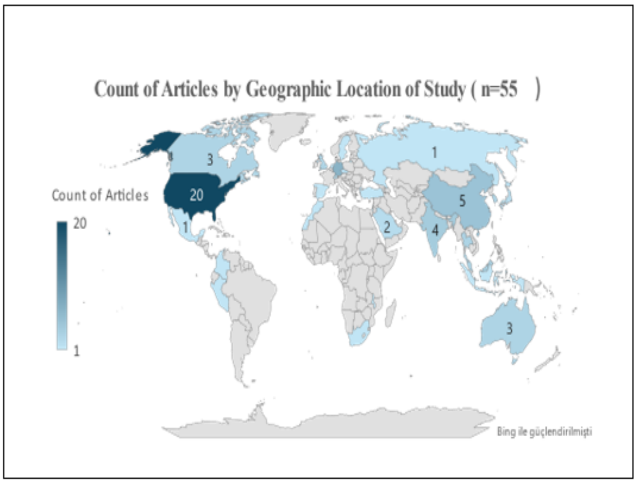

Figure 2. Count of articles according to the study's geographic location.

Table 5. Journals where the selected articles were published the most.

Journal Name	Count of Articles
Technology in Society (Technology in Society, 2024)	10
Drones (Drones,2024)	4
Cogent Business and Management (Cogent Business & Management ǀ Taylor & Francis Online, 2024)	2
International Journal of Logistics Research and Applications (International Journal of Logistics Research & Applications, 2024).	2
Others	37

Table 6. shows the subject distribution of the studies included in this review. The definitions of the subject areas were developed based on the information from the Scopus database and the Google Scholar search engine.

It was noted that the articles subject to our research could fall into more than one subject area in the database, as specified in the table of article distribution by subject area. In this respect, the subject distribution of the studies is more comprehensive.

Note: Certain articles are included in more than one subject category.

Table 7. shows the citation status of the reviewed articles. As seen in the table, the article by Chung et al. (Chung et al., 2020) titled ‘‘Optimization for drone and drone – truck combined operations: A review of the state of the art and future directions’’ was the most cited one.

Table 6. Distribution of the selected articles by subject.

Subject Area	Count of Articles
Social Sciences	24
Business, Management, and Accounting	21
Engineering	14
Computer Science	14
Decision Sciences	8
Environmental Sciences	3
Medicine	3
Earth and Planetary Sciences	3
Agricultural and Biological Sciences	2
Mathematics	2
Psychology	2
Economics, Econometrics, and Finance	2
Others	2

Table 7. Articles with the highest number of citations.

Document Title	Authors	Year	Source
Optimization for drone and drone-truck combined operations: A review of the state of the art and future directions (Chung et al., 2020).	Chung, S.H., Sah, B., Lee, J.	2020	246
The societal impact of commercial drones (Rao et al., 2016).	Rao, B., Gopi, A.G., Maione, R	2016	236
Drones for parcel and passenger transportation: A literature review (Kellermann et al., 2020)	Kellermann, R., Biehle, T., Fischer, L.	2020	208
Drone delivery: Factors affecting the public's attitude and intention to adopt (Yoo et al., 2018).	Yoo, W., Yu, E., Jung, J.	2018	190
Public acceptance of drones: Knowledge, attitudes, and practice (Aydin, 2019)	Aydin, B.	2019	132
Analysis of barriers to implement drone logistics (Sah et al., 2021)	Sah, B., Gupta, R., Bani-Hani, D.	2021	99
Public acceptance of drone applications in a highly urbanized environment (Tan et al., 2021)	Lin Tan, L.K., Lim, B.C., Park, G., Low, K.H., Seng Yeo, V.C.	2021	64
The acceptance of civil drones in Germany (Eißfeldt et al., 2020)	Eißfeldt, H., Vogelpohl, V., Stolz, M., (...), Belz, J., Kügler, D.	2020	64
Critical factors characterizing consumers’ intentions to use drones for last-mile delivery: Does delivery risk matter?(Osakwe et al., 2022)	Osakwe, C.N., Hudik, M., Říha, D., Stros, M., Ramayah, T.	2022	62
The View from Above: A Survey of the Public’s Perception of Unmanned Aerial Vehicles and Privacy (Nelson et al., 2019)	Nelson, J.R., Grubesic, T.H., Wallace, D., Chamberlain, A.W.	2019	41

4. Discussion

With technological developments, societies also adapt to these developments positively or negatively. The use of UAVs, which have become a symbol of these technological developments, increases every year. Therefore, the number of studies on public perceptions of UAV use increases steadily with the rise in their use (Nelson et al., 2019).

The current section explains the factors affecting the public perception of UAVs, revolving around thematic clusters. In this regard, Table 8. presents the thematic clusters related to the public acceptance of UAVs based on the publications reviewed.

Table 8. Thematic classification of the factors related to the public perception of UAVs.

Category	Theme
Regulatory Factors	Privacy
	Security
	Safety
Operational Factors	Purpose and Place of Use
External Factors	Media Use
	Source and Impact of Information
Economic Factors	Usefulness
	Related Infrastructure and Services

4.1. Regulatory Factors

Upon reviewing the studies on the public perception of UAVs, the violation of private life, privacy concerns, and safety and security risks come to the forefront because the risk perception regarding UAVs can be expressed as physical security concerns. In this regard, two different thoughts can be established. The first is the unlimited use of UAVs, and the other is the use of UAVs for the public good (Komasová et al., 2020) . The public perception of UAVs also varies according to the areas of use of these vehicles. However, even if the efficient areas of use are given as examples and the evaluation is performed accordingly, the results change (Del-Real and Díaz-Fernández, 2021).

4.2. Operational Factors

Nowadays, UAVs are utilized primarily for surveillance and analysis purposes, particularly for aerial imaging and image analysis. They are used in diverse areas, such as aerial imaging, search and rescue, fire extinguishing, traffic inspections, agricultural activities, and for hobby and commercial purposes. Aerial photography is widely used among these. When examined in terms of operational factors, the public approaches the use of UAVs more positively in terms of their use for the public good. Although society displays a positive attitude toward the use of UAVs for the public good, the most significant concern here is individuals' privacy concerns. Moreover, the easy accessibility of UAVs is another source of concern for society (Rao et al., 2016).

4.3. External Factors

The way the media depicts UAVs considerably impacts the public perception of UAVs. The media is one of the most important and effective elements forming the image of UAVs perceived by society. Positive or negative news about UAVs influences or changes the level of knowledge and attitude of the public toward these vehicles. Negative depictions concerning security may cause fear and anxiety about UAVs; however, positive examples, such as search and rescue scenarios, may bring the advantages of these technologies to the forefront (Richards, 2018).

4.4. Economic Factors

Economic studies on the public perception of UAVs have usually included the acceptance of their delivery and commercial services. When considered in logistic terms, distribution centers located far from the city make delivery challenging. While the delivery of cargo by UAVs directly to the address may create problems that can affect society, the desire for fast delivery without being stuck in traffic flow has caused the public's thoughts to differentiate. It would be beneficial to indicate that there are still question marks about privacy among positive thoughts (Toraman and Öz, 2023).

5. Conclusion

The current study presents a systematic literature review on the perceptions of individuals, commercial organizations, states, and researchers regarding the use of UAVs between 2015 and 2024 and focuses on how this perception is understood in literature sources.

The study attempts to eliminate research gaps. In this respect, our study can help researchers analyze the current situation on the issue and then contribute to future research (Mohsan et al., 2022). Considering the public perceptions of UAVs, it is seen that studies have been conducted on factors, such as privacy, attitude, concern, risk, and acceptance. It is thought that policymakers and other stakeholders will benefit from these concepts in making decisions about the future (Nakamura & Kajikawa, 2018).

While numerous studies have investigated public perception of UAVs in specific contexts or applications, a comprehensive and systematic analysis of the literature that synthesizes these diverse findings across domains remains limited. Prior studies typically focus on narrow aspects such as particular applications (e.g., delivery services, as in Yoo et al., 2018), specific geographical contexts (e.g., urban environments, as in Tan et al., 2021), or individual factors affecting acceptance (e.g., privacy concerns, as in Nelson et al., 2019).

The existing literature lacks a holistic framework that integrates these disparate findings into a coherent understanding of the multidimensional factors influencing public perception of UAVs. Specifically, the following gaps are addressed by our systematic review:

Integration across application domains: Unlike previous reviews that concentrate on single application areas, our analysis synthesizes findings across diverse UAV applications, from agricultural use to urban delivery to emergency response.

Temporal evolution analysis: This study uniquely tracks how public perception has evolved from 2015 to 2024, capturing the trajectory of societal attitudes as UAV technology has become more prevalent.

Thematic classification framework: We develop a novel classification scheme (regulatory, operational, external, and economic factors) that provides a structured approach to understanding the multifaceted nature of public perception toward UAVs.

Geographical perspective: By analyzing studies across different countries and regions, our review offers insights into how cultural, regulatory, and societal contexts influence UAV acceptance patterns globally.

Interdisciplinary synthesis: This study bridges disciplinary boundaries by synthesizing research from technical fields (engineering, computer science), social sciences, business studies, and environmental research.

By addressing these gaps, our systematic literature analysis contributes to the field by establishing a foundation for future research on UAV societal acceptance. It provides stakeholders—including policymakers, UAV manufacturers, service providers, and researchers—with a comprehensive understanding of the multidimensional factors that shape public perception, enabling more informed approaches to UAV implementation, regulation, and community engagement.

Upon examining the issues related to how the public perception of UAVs is understood in the literature, it was seen that the application or use of UAVs, even for the public good, currently creates a risk in society. It can be said that thoughts about using UAVs for the public good, such as search and rescue, fire extinguishing, or border security, change with a change in demographic factors. It is evident that the public is concerned about the use of these vehicles for hobby or commercial purposes outside of public interest, particularly aerial imaging. It would be beneficial for the competent authorities to improve their work by taking these concerns into account in the future.

Authors' Contribution

The authors declare that they have contributed equally to the article.

Conflict of Interest Statement

There is no conflict of interest among the authors.

Research and Publication Ethics Statement

The study has been conducted in accordance with research and publication ethics

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