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Enhancing UAV Crew Performance and Safety: A Technology and Innovation Management Perspective

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Abstract

The integration of Unmanned aerial vehicles (UAVs) into various sectors underscores the importance of optimizing human factors to ensure operational efficiency, safety, and mission success. This study presents a comprehensive bibliometric analysis of the literature on human factors in UAV operations, focusing on cognitive workload, situational awareness, decision-making, ergonomic design, and human-machine interaction. The analysis was conducted using the WoS, covering publications from 2000 to 2023. Key findings include a significant increase in research output over the last decade, highlighting the growing interest and investment in UAV technology and human factors. Influential authors such as Rosenstein (2006), Patterson (2010), Reason (1990), Wiegmann (2001), and Shappell (2007), along with institutions like Beijing University of Posts and Telecommunications, Southeast University China, Xidian University, and Nanjing University of Aeronautics and Astronautics, have emerged as leaders in this field, contributing to advancements in ergonomic design and decision-making processes. Notably, there is a lack of comprehensive studies addressing the long-term cognitive workload effects on UAV operators and the development of standardized ergonomic guidelines tailored specifically for UAV operation environments. The integration of advanced human-machine interaction technologies remains underexplored, indicating a need for further research in this area. By highlighting these gaps, the analysis provides a nuanced understanding of current research dynamics, offering valuable implications for UAV operators, regulators, and policymakers. These findings are pivotal for advancing the field and guiding future research initiatives aimed at enhancing crew performance and safety in UAV operations.

Keywords: unmanned aerial vehicles, innovation management, human factors, crew performance, safety

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İnsansız Hava Araçları (İHA) Mürettebat Performansı ve Emniyetin Artırılması: Teknoloji ve İnovasyon Yönetimi Perspektifi

Öz

İnsansız hava araçlarının (İHA) çeşitli sektörlere entegrasyonu, operasyonel verimliliği, emniyeti ve görev başarısını sağlamak için insan faktörlerinin optimize edilmesinin önemini vurgulamaktadır. Bu çalışma, İHA operasyonlarında insan faktörleri üzerine yapılan literatürün kapsamlı bir bibliyometrik analizini sunmakta ve bilişsel iş yükü, durumsal farkındalık, karar verme, ergonomik tasarım ve insan-makine etkileşimi konularına odaklanmaktadır. Analiz, 2000-2023 yılları arasındaki yayınları kapsayacak şekilde Web of Science kullanılarak gerçekleştirilmiştir. Ana bulgular arasında, son on yılda araştırma çıktılarında önemli bir artış olduğu, İHA teknolojisi ve insan faktörlerine olan artan ilgi ve yatırımı vurgulayan sonuçlar yer almaktadır. Rosenstein (2006), Patterson (2010), Reason (1990), Wiegmann (2001) ve Shappell (2007) gibi etkili yazarlar ile Beijing University of Posts and Telecommunications, Southeast University China, Xidian University, ve Nanjing University of Aeronautics and Astronautics gibi kurumlar, bu alanda lider olarak ortaya çıkmış ve ergonomik tasarım ve karar verme süreçlerinde ilerlemelere katkıda bulunmuşlardır. Özellikle, İHA operatörlerinin uzun vadeli bilişsel iş yükü etkilerini ele alan kapsamlı çalışmaların ve İHA operasyon ortamlarına özel olarak uyarlanmış standart ergonomik kılavuzların geliştirilmesinin eksikliği dikkat çekicidir. Gelişmiş insan-makine etkileşimi teknolojilerinin entegrasyonu halen yeterince araştırılmamış olup, bu alanda daha fazla araştırmaya ihtiyaç olduğunu göstermektedir. Bu boşlukları vurgulayan analiz, mevcut araştırma dinamiklerini anlayışlı bir şekilde sunarak İHA operatörleri, düzenleyiciler ve politika yapıcılar için değerli çıkarımlar sağlamaktadır. Bu bulgular, alanın ilerlemesi ve İHA operasyonlarında ekip performansı ve güvenliği artırmaya yönelik gelecekteki araştırma girişimlerine rehberlik etmek açısından önemlidir.

Anahtar Kelimeler: insansız hava araçları, inovasyon yönetimi, insan faktörleri, mürettebat performansı, emniyet

1. INTRODUCTION

The proliferation of unmanned aerial vehicles (UAVs) has revolutionized various sectors, including military operations, agriculture, logistics, environmental monitoring, and emergency response. (Sharma et al., 2022) As UAV technology advances, the complexity and scope of their applications expand, necessitating a deeper understanding of the human factors that influence UAV operations (Shoufan et al., 2018). Human factors, encompassing cognitive workload, situational awareness, decision-making processes, ergonomic design, and the human-machine interface, play a critical role in determining the safety and effectiveness of UAV missions (Swaminathan et al., 2022). The role and importance of human factors in UAV operations cannot be overstated. As UAV technology becomes more sophisticated, the interaction between humans and these systems becomes increasingly complex (Zak et al., 2023). Human factors such as cognitive workload, situational awareness, decision-making, ergonomic design, and the human-machine interface directly impact the safety, efficiency, and success of UAV missions (Sharma et al., 2022). High cognitive workload can lead to operator fatigue and errors, while good situational awareness enables operators to make informed decisions in dynamic environments (De Almeida et al., 2021). Effective decision-making processes are crucial for responding to unexpected situations and ensuring mission objectives are met. Ergonomic design and a well-designed human-machine interface enhance operator comfort and efficiency, reducing the likelihood of mistakes and improving overall performance (Swaminathan et al., 2022). Understanding and optimizing these human factors are essential for maximizing the potential of UAVs across various applications, ensuring that they are not only technologically advanced but also safe and effective in real-world operations. This underscores the critical need for continued research and development in the field of human factors in UAV operations (Shoufan et al., 2018). From the perspective of technology and innovation management, optimizing these human factors is essential for enhancing crew performance and safety (Tiansawat and Elliott, 2020) Effective management of human factors can lead to improved operational efficiency, reduced risk of accidents, and better overall mission outcomes (De Almeida et al., 2021). This paper aims to provide a comprehensive bibliometric analysis of the literature on human factors in UAV operations, highlighting key issues and research trends that are critical for advancing the field. The analysis identifies the most significant publications and authors, maps the evolution of research trends over time, and examines collaborative networks among researchers and institutions. Additionally, it uncovers the most frequently used keywords and themes in the literature and identifies the leading journals and conferences where relevant research is published. These insights are invaluable for UAV operators, regulators, and policymakers in making informed decisions and developing best practices for UAV operations.

The objectives of this bibliometric analysis are multifaceted (Alqurashi et al., 2022) First, it aims to identify the most influential publications and authors, pinpointing key studies and researchers who have significantly contributed to the understanding of human factors in UAV operations. This involves recognizing foundational works and thought leaders in the field.

Second, the study seeks to determine research trends and their evolution over time by analyzing the progression of research themes, thus understanding how the focus on different human factors has evolved. Third, it examines collaborative networks among researchers and institutions to reveal key partnerships and influential research groups, providing insight into the dynamics of academic and practical collaboration. Fourth, the analysis discovers the most frequently used keywords and themes, identifying common terms that help understand the main areas of focus within the literature. Fifth, it highlights the leading journals and conferences, recognizing the primary platforms for disseminating research findings and staying updated with the latest advancements in the field. By synthesizing these findings, this paper provides a detailed overview of the current state of research on human factors in UAV operations, offering valuable insights for future research and practical applications in the industry.

2. BACKGROUND

The rapid advancement and widespread adoption of unmanned aerial vehicles (UAVs) have transformed numerous sectors, including military operations, agriculture, logistics, environmental monitoring, and emergency response (Chen et al., 2022) As UAV technology continues to evolve, so too does the complexity and scope of their applications, necessitating a deeper understanding of the human factors that influence UAV operations (Geraci et al., 2018). Human factors encompass a range of elements, such as cognitive workload, situational awareness, decision-making processes, ergonomic design, and the human-machine interface (Gong et al., 2022). These factors are crucial in determining the safety and effectiveness of UAV missions. From the perspective of technology and innovation management, optimizing human factors is essential for enhancing crew performance and ensuring the safety and success of UAV operations (Geraci et al., 2018). Effective management of human factors can lead to improved operational efficiency, reduced risk of accidents, and better overall mission outcomes. (Grlj et al., 2022) Recognizing the importance of these factors, there has been a significant body of research dedicated to exploring various aspects of human interaction with UAV systems (Lu et al., 2022). The existing literature on human factors in UAV operations covers a wide array of topics, including but not limited to, the impact of cognitive workload on operator performance (Lv et al.,2021).

Strategies for maintaining situational awareness, the role of ergonomic design in minimizing operator fatigue, and the effectiveness of different human-machine interfaces (Mohsan et al., 2022). This body of work provides valuable insights into the challenges and solutions associated with UAV operations, guiding both academic research and practical applications in the field (Mozaffari et al., 2019). However, despite the substantial amount of research conducted, there is a need for a comprehensive bibliometric analysis to systematically map the landscape of this literature (Poudel and Moh, 2022). Such an analysis can identify the most influential publications and authors, uncover research trends over time, and highlight key collaborative networks among researchers and institutions (Rovira-Sugranes et al., 2022). Moreover, it can reveal the most frequently used keywords and themes and identify the leading journals and conferences where relevant research is published (Wang et al., 2022). These insights are invaluable for UAV operators, regulators, and policymakers in making informed decisions and developing best practices for UAV operations (Zhang et al., 2022a). This paper aims to fill this gap by providing a detailed bibliometric analysis of the literature on human factors in UAV operations. By doing so, it seeks to offer a clear understanding of the current state of research, identify areas that require further investigation, and provide a foundation for future studies. Through a systematic examination of the existing literature, this study will highlight critical issues and research trends that are essential for advancing the field and optimizing the integration of human factors in UAV operations.

This study includes several sections to provide a comprehensive analysis of human factors in UAV operations. The first section, Introduction, outlines the importance of UAV technology and the role of human factors in ensuring safe and effective operations. The second section, Background, delves into the advancements in UAV technology and the significance of human factors. The third section, Research Method, describes the bibliometric analysis methodology, including data collection, filtering processes, and analytical techniques. The fourth section, Findings, presents the results of the bibliometric analysis, highlighting key trends, influential publications, and collaborative networks. The fifth section, Discussion and Conclusion, interprets the findings, discusses their implications for UAV operators, regulators, and policymakers, and provides recommendations for future research and practical applications. By structuring the study in this manner, the paper aims to guide readers through the various aspects of human factors in UAV operations, offering a detailed and organized overview of the research landscape.

2.1. Importance of UAV Technology

Unmanned aerial vehicles (UAVs), commonly known as drones, have experienced rapid technological advancements and a corresponding rise in adoption across various sectors (Zhang et al., 2022b). Originally developed for military applications, UAVs have expanded into civilian and commercial uses, providing versatile solutions for a wide range of challenges. In the military domain, UAVs offer capabilities for surveillance, reconnaissance, and precision strikes, reducing the risk to human life (Zhu et al., 2022). Beyond defense, UAVs are transforming industries such as agriculture, where they enable precision farming techniques, including crop monitoring and pesticide application, leading to increased yields and reduced resource use (Chen et al., 2022). In logistics, UAVs are revolutionizing delivery systems by providing quick and efficient transportation of goods, particularly in remote or hard-to-reach areas. Environmental monitoring benefits from UAVs through enhanced capabilities for data collection, enabling detailed analysis of ecosystems, wildlife tracking, and disaster management (Poudel and Moh, 2022). Emergency response teams use UAVs to assess disaster-stricken areas, facilitate search and rescue operations, and deliver medical supplies to inaccessible locations (Grlj et al., 2022). The flexibility, efficiency, and cost-effectiveness of UAV technology continue to drive its integration into these diverse applications, underscoring its growing importance in modern society (Alqurashi et al., 2022).

2.2. Significance of Human Factors in UAV Operations

As UAV technology becomes more sophisticated, the complexity of their operation increases, making the role of human factors critical in ensuring the safety and effectiveness of UAV missions. Human factors refer to the study of how humans interact with systems and devices, encompassing elements such as cognitive workload, situational awareness, decision-making processes, ergonomic design, and the human-machine interface (Sharma et al., 2022). These factors significantly influence the performance of UAV operators and the overall success of UAV operations (Shoufan et al., 2018). Cognitive workload pertains to the mental demands placed on UAV operators, who must process a vast amount of information and make timely decisions (Swaminathan et al., 2022). High cognitive workload can lead to errors, decreased performance, and accidents. Situational awareness is the operator's ability to perceive and understand the UAV's status and the environment, crucial for effective decision-making and mission success (Tiansawat and Elliott, 2020). Ergonomic design of UAV control stations and interfaces impacts operator comfort and efficiency, reducing fatigue and enhancing performance (Ubina and Cheng, 2022). The human-machine interface, encompassing the design and functionality of the controls and displays, affects how intuitively operators can manage UAVs and respond to situations (Wang et al., 2022). Optimizing these human factors is essential for enhancing crew performance, minimizing risks, and ensuring the success of UAV operations (Yan et al., 2022). Addressing these factors through research and development can lead to improved operational efficiency, reduced risk of accidents, and better overall mission outcomes. Understanding and managing human factors are thus vital for advancing UAV technology and its applications.

3. RESEARCH METHOD

Bibliometric analysis, utilizing quantitative measurements, is a powerful method for analyzing and understanding scientific publications. This technique operates on the premise that patterns and trends in the literature can provide crucial insights into the state of a particular field, including its evolution, research trends, and key contributors (Donthu et al., 2021). In this context, incorporating the PRISMA approach is also essential. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement helps systematic reviewers report their review’s purpose, methodology, and findings transparently, reflecting advances in systematic review methodology and terminology over the past decade (Page et al., 2021). Bibliometric analysis, alongside PRISMA, is applicable to a wide range of disciplines, including science, technology, health, and the social sciences. This analysis involves creating graphical representations of bibliographic material by mapping keywords, countries, and authors through bibliographic coupling and co-citation analysis using visualization software (Moher et al., 2015). Statistical methods for interpreting results often include systematic reviews and, when feasible, meta-analyses (Moher et al., 2010). While a systematic review entails a thorough search and synthesis of all published reports on a topic, the present study, with data limited to 5422 items, does not fall within the scope of a meta-analysis. In this study, the filtering process included language selection, which can be a significant constraint. The search language was restricted to English, excluding potentially relevant studies published in other languages. The inclusion criteria encompassed peer-reviewed articles, conference papers, and significant works within the scope of human factors in UAV operations. Exclusion criteria involved duplicate records, which were meticulously identified and removed, as well as studies with incorrect or incomplete data entries. Furthermore, only documents indexed in the Web of Science database were considered, potentially overlooking relevant research available in other databases. These limitations and filtering choices are crucial to understand the scope and boundaries of the analysis, ensuring clarity and transparency in the research process.

3.1. Data Collection

The bibliometric analysis in this study, guided by the structure and presentation of items from the PRISMA flow chart, is systematic. It involves gathering a dataset of publications, such as articles, books, or patents, and then analyzing and interpreting the data using various quantitative metrics (McBurney and Novak, 2002). Key metrics include:

Citation Counts: Measures the frequency with which a publication has been referenced by other papers, helping to identify prominent authors, organizations, and widely cited publications within the field (Moed et al., 2012).

Co-Citation Analysis: Examines the similarities in the citation patterns of different publications, detecting clusters of articles that share highly connected research subjects and themes, thus highlighting influential works and research areas (Aksnes et al., 2019).

Co-Authorship Analysis: Quantifies the number of articles co-authored by multiple authors, identifying the most collaborative authors and institutions within a subject, and shedding light on the collaborative dynamics of the research community (Ponomariov and Boardman, 2016).

Network Analysis: Assesses the connections between various publications, authors, and institutions, identifying significant actors and research issues within a subject, and providing insights into the structure and dynamics of the research network (Van Duijn and Vermunt, 2006).

Bibliometric analysis employs a wide range of analytical and descriptive techniques to perform quantitative analysis. This study utilizes these techniques to systematically map the landscape of research on human factors in UAV operations, drawing on a comprehensive dataset of scientific publications.

Table 1. The methodological summary

Unit of Analysis	Journal articles that discuss "human factors" and "UAV operations"
Type of Analysis	Bibliometric Analysis
Period of Analysis	2004-2024
Query String	TS=("human factors" OR "cognitive workload" OR "decision-making" OR "communication" OR "situational awareness") AND ("UAV" OR "unmanned aerial vehicle" OR "drone") AND ("operations" OR "safety" OR "performance")
Total Number of Articles	5422

Table 1 highlights the key components and scope of the bibliometric analysis conducted in this study. By leveraging these bibliometric techniques, the study aims to provide a detailed understanding of the current state of research on human factors in UAV operations, identifying key publications, authors, and research trends, and offering valuable insights for future research and practical applications in the industry. A detailed search query was formulated to capture the wide range of factors influencing UAV operations. The query combined terms related to human factors, UAVs, and various aspects of their operations to ensure a holistic search. For the analysis and visualization phase, the bibliometric data extracted from the Web of Science database was first prepared and imported into VOSviewer in CSV or text format. This prepared dataset allowed for various types of bibliometric analyses. Web of Science was chosen for this study due to its comprehensive and authoritative coverage of scholarly literature across a wide range of disciplines. It is one of the most extensive databases for academic research, ensuring a significant proportion of relevant research in the field of human factors in UAV operations is included. The trends analysis was conducted to plot the number of publications per year, revealing temporal trends and patterns in the research on human factors in UAV operations.

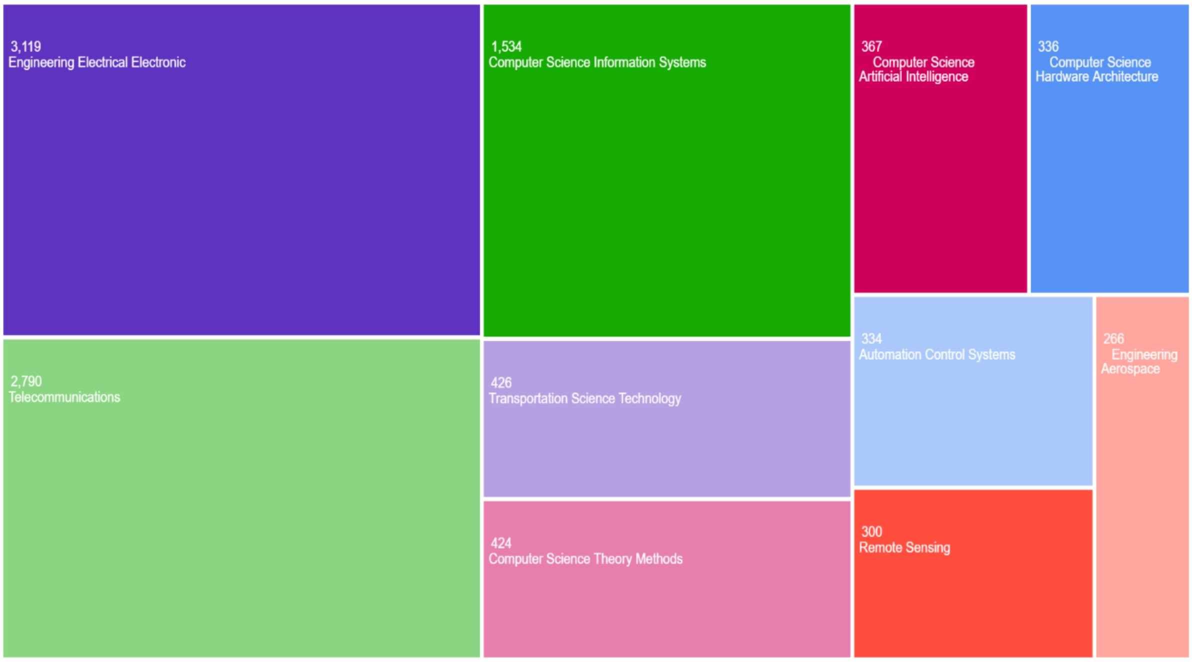
To identify influential papers and authors, citation networks were created using the citation analysis feature. This analysis highlighted key contributions and seminal works in the field. The co-authorship networks mapped collaborative relationships among researchers, identifying prominent research groups and collaborations. Additionally, the keyword analysis utilized the keyword co-occurrence analysis feature to visualize key themes and topics in the literature, providing an overview of the primary areas of focus within the research landscape. This comprehensive approach facilitated a detailed understanding of the development and current state of research on human factors in UAV operations.

4. FINDINGS

The findings of this study offer a comprehensive overview of the current landscape of research on human factors in UAV operations. Through meticulous bibliometric analysis, key insights have been uncovered regarding the evolution of research trends, influential publications and authors, and the collaborative networks within this field. The analysis highlights significant shifts in focus areas over time, reflecting advancements in UAV technology and the increasing importance of optimizing human factors to enhance operational safety and performance. By examining citation counts, co-citation patterns, and co-authorship networks, the study identifies prominent contributors and seminal works that have shaped the discourse on human factors in UAV operations.

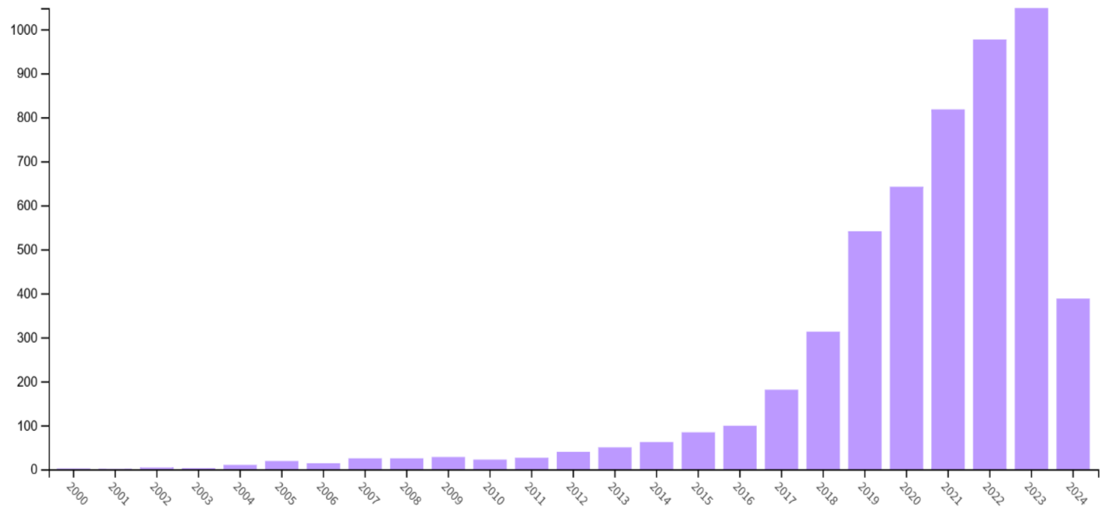
Additionally, keyword analysis provides a detailed understanding of the primary themes and topics that have dominated the research landscape, offering a clear picture of the areas that have garnered the most attention from the academic and professional communities. These findings not only elucidate the current state of the field but also provide valuable direction for future research, helping to identify gaps and emerging trends that warrant further investigation. Through this detailed exploration, the study aims to support UAV operators, regulators, and policymakers in making informed decisions and developing best practices that prioritize human factors for safer and more efficient UAV operations.

Treemap Chart 1. Web of science categories



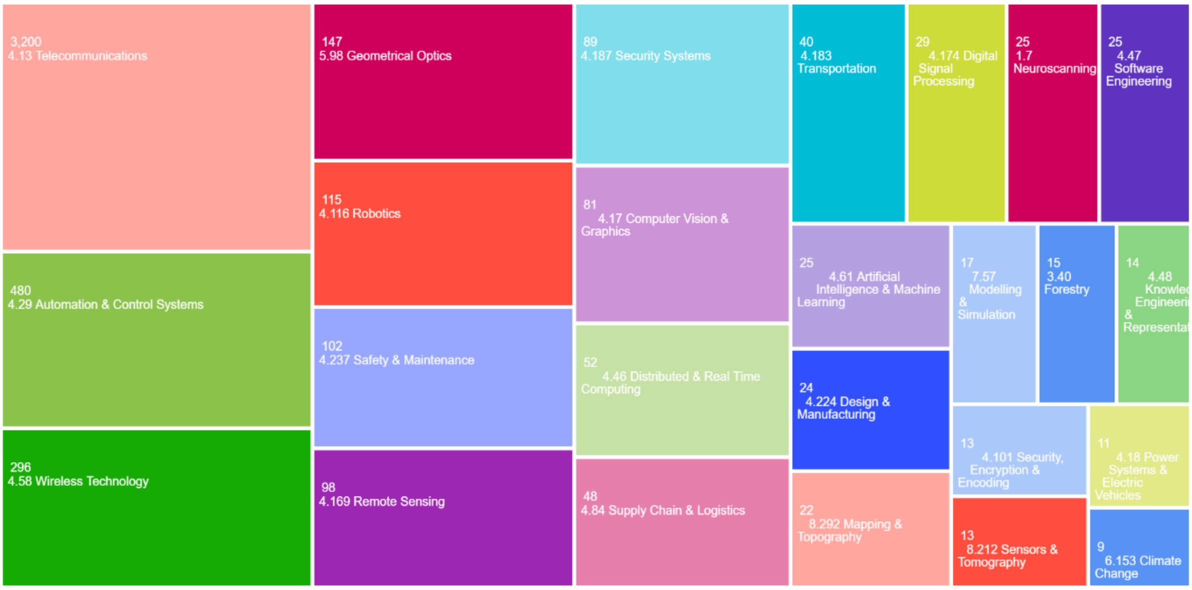
Treemap Chart 1 represents the distribution of records across various categories within the Web of Science database, specifically related to the field of Electrical and Electronic Engineering. The highest representation is in the Engineering Electrical Electronic category, which comprises 3,119 records, accounting for 57.504% of the total 5,424 records. Telecommunications follows with 2,790 records, making up 51.438% of the total. These two categories alone encompass over half of the records, indicating a strong focus on these areas. Significant contributions are also observed in the Computer Science subfields. Computer Science Information Systems has 1,534 records (28.282%), while other subfields like Computer Science Theory Methods (424 records, 7.817%), Artificial Intelligence (367 records, 6.766%), and Hardware Architecture (336 records, 6.195%) also show substantial representation. Transportation Science Technology has 426 records, contributing 7.854% of the total 5,424 records in the field of Electrical and Electronic Engineering. Additional notable categories include Automation Control Systems with 334 records (6.158%) and Remote Sensing with 300 records (5.531%). Smaller yet significant categories include Engineering Aerospace (266 records, 4.904%), Instruments Instrumentation (241 records, 4.443%), and Robotics (209 records, 3.853%). Categories such as Physics Applied, Engineering Multidisciplinary, and Chemistry Analytical each contribute around 3% or less. The least represented categories, each comprising around 1% or less of the total records, include Engineering Civil, Engineering Mechanical, Environmental Sciences, and Geosciences Multidisciplinary. Overall, this data reflects a broad diversity of research areas within the Electrical and Electronic Engineering field, with a predominant focus on core areas like Electrical Engineering and Telecommunications, while also highlighting significant activity in various subfields of Computer Science and other specialized engineering and science disciplines.

Bar Chart 1. Final publication year



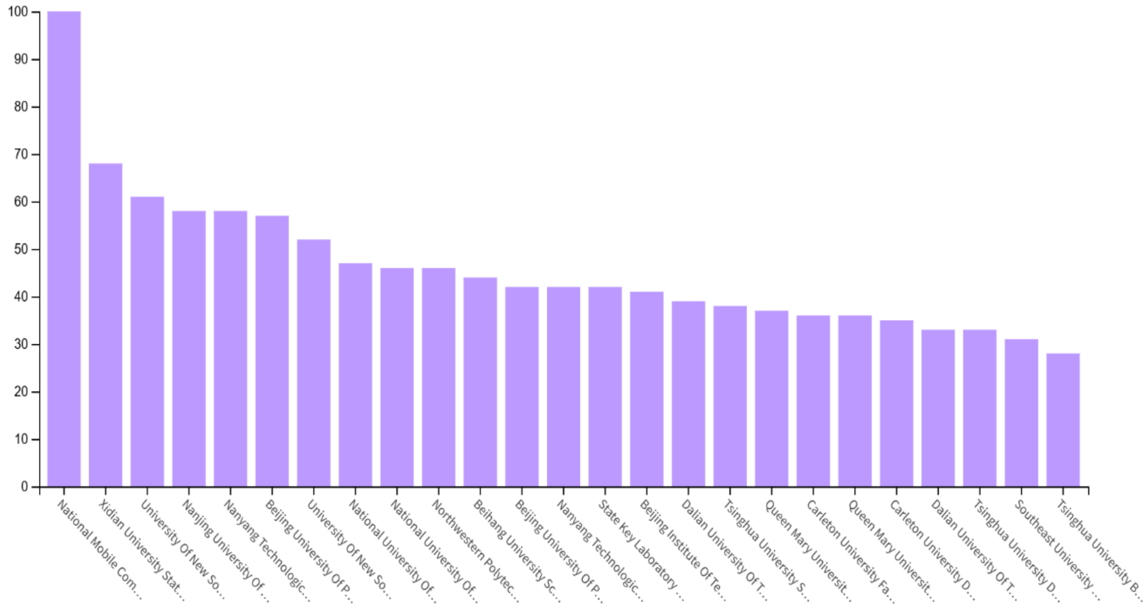
Bar Chart 1 represents the distribution of records across various publication years in the Web of Science database, specifically related to the field of Electrical and Electronic Engineering. The number of records has seen a significant increase in recent years, with 2023 having the highest count at 1,048 records, accounting for 19.322% of the total 5,424 records. This is followed by 2022 with 977 records (18.013%) and 2021 with 818 records (15.081%). The year 2024 has 388 records so far, making up 7.153%. The mid-2010s also show a steady increase, with 541 records in 2019 (9.974%) and 313 records in 2018 (5.771%). Earlier years, such as 2015 to 2017, have lower counts, ranging from 84 records (1.549%) in 2015 to 181 records (3.337%) in 2017. The early 2010s and late 2000s have even fewer records, with numbers gradually decreasing as we go further back. The early 2000s have the fewest records, indicating less research activity in this field during that period. Overall, the data reflects a rising trend in research publications in Electrical and Electronic Engineering, with a sharp increase in recent years, highlighting a growing global focus and advancements in this field. The significant increase in records from 2020 to 2023 in Electrical and Electronic Engineering can be attributed to several factors. The rapid advancements in technologies like 5G, AI, and IoT drove extensive research and development. The COVID-19 pandemic accelerated the adoption of digital and remote solutions, increasing the need for improved electronic systems. Additionally, global initiatives for sustainable energy prompted research into energy-efficient technologies. Increased funding and collaboration opportunities further supported this growth. Overall, the rise in publications reflects technological innovation, societal needs, and greater investment in research.

Treemap Chart 2. Research areas



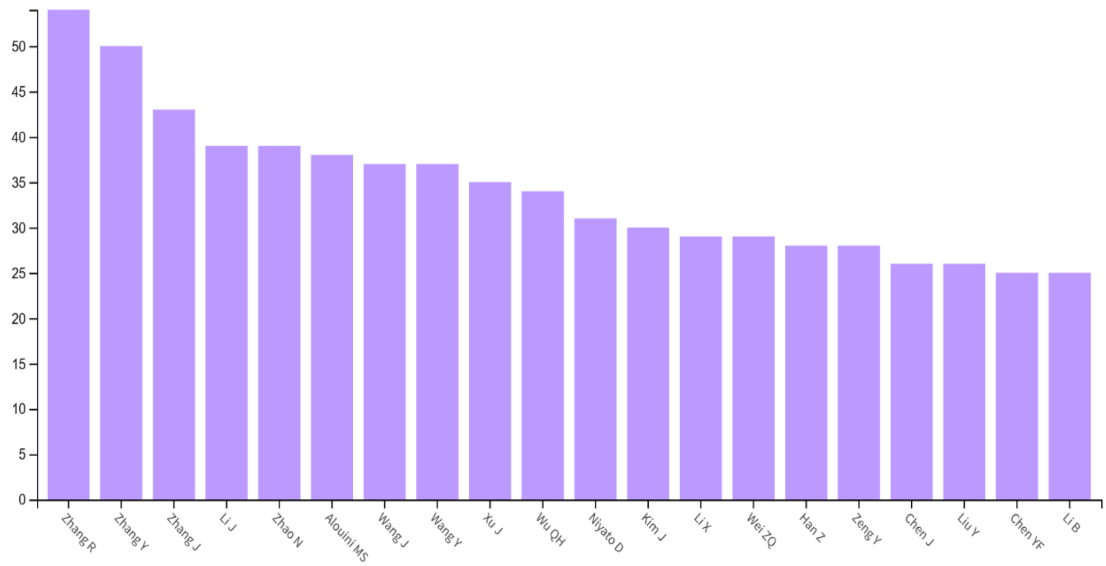
The bibliometric analysis revealed a diverse range of research topics within the dataset of 5,422 articles as seen Treemap Chart 2. The most prominent category was "Telecommunications," encompassing 58.997% of the total articles, indicating a significant focus on this area. "Automation & Control Systems" followed with 8.850%, highlighting its substantial yet smaller proportion compared to telecommunications. Several other key fields were identified, though with smaller percentages. "Wireless Technology" accounted for 5.457%, showing a moderate emphasis on advancements in wireless communication. Fields like "Geometrical Optics" and "Robotics" represented 2.710% and 2.120%, respectively, illustrating their niche yet important roles in the broader research landscape. Categories such as "Safety & Maintenance," "Remote Sensing," and "Security Systems" were also notable, each contributing around 1.881%, 1.807%, and 1.641% of the articles. These topics are crucial for ensuring operational reliability and security in technological applications. Other areas like "Computer Vision & Graphics" (1.493%) and "Distributed & Real Time Computing" (0.959%) highlight the ongoing interest in enhancing computational capabilities and visual processing technologies. "Supply Chain & Logistics" (0.885%) and "Transportation" (0.737%) further emphasize the integration of technological advancements into practical applications. Less prominent but still significant areas include "Digital Signal Processing" (0.535%), "Neuroscanning" (0.461%), and "Artificial Intelligence & Machine Learning" (0.461%), reflecting the expanding influence of advanced processing and AI technologies. The analysis also covered specialized fields with even smaller representations, such as "Quantum Mechanics" (0.129%), "Climate Change" (0.166%), and "Sustainability Science" (0.074%). These areas, while not as heavily represented, are critical for addressing specific scientific and societal challenges. In summary, the bibliometric analysis shows a broad and varied landscape of research interests, with a predominant focus on telecommunications and significant contributions from fields related to automation, wireless technology, and safety. The diversity of topics underscores the interdisciplinary nature of current research efforts, aiming to address both technological advancements and practical applications across multiple domains.

Bar Chart 2. Top institutions by publication count in UAV operations and human factors research



Bar Chart 2 illustrates a notable dominance of Chinese institutions in the realm of research or publication output, with Beijing University of Posts and Telecommunications leading at 180 occurrences, accounting for 3.319% of the total. Following closely are Southeast University China, Xidian University, and Nanjing University of Aeronautics and Astronautics, highlighting China's strong emphasis on technology and engineering disciplines. International representation includes prominent institutions like the University of London and the University of New South Wales, underscoring the global nature of research in these fields. Additionally, institutions with a focus on defense and technology, such as the Army Engineering University of PLA and the National University of Defense Technology China, feature prominently. This dataset not only underscores the significant contributions from Chinese universities but also reflects the collaborative and international efforts in advancing research across technology and defense sectors.

Bar Chart 3. Top authors by publication count in UAV operations and human factors research



Bar Chart 3 highlights the prolific contributions of individual authors in a dataset comprising 5,424 records. Among the most prominent, Zhang R stands out with 54 records, making up 0.996% of the total, closely followed by Zhang Y with 50 records (0.922%) and Zhang J with 43 records (0.793%).

The data showcases a notable presence of authors with common Chinese surnames such as Zhang, Li, Wang, and Chen, indicating significant research output from Chinese scholars. Noteworthy contributions also come from international researchers like Alouini MS, who has 38 records (0.701%), and Niyato D with 31 records (0.572%). Other significant contributors include Kim J (30 records, 0.553%), Wei ZQ, and Han Z (both with 28 records, 0.516%). The presence of multiple authors with the same last names but different initials, such as Li J, Li X, and Li B, points to the commonality of these surnames in the research community. This dataset reflects a diverse and extensive participation from researchers globally, with a significant representation from Chinese academics, underscoring their substantial role in the field.

The bibliometric analysis provided a comprehensive overview of the structural and dynamic characteristics of the research field, highlighting the developments and influential contributions within the domain of human factors and related topics. The analysis highlights significant shifts in focus areas over time, reflecting advancements in UAV technology and the increasing importance of optimizing human factors to enhance operational safety and performance. By examining citation counts, co-citation patterns, and co-authorship networks, the study identifies prominent contributors and seminal works that have shaped the discourse on human factors in UAV operations. The visualization of academic citations through bibliographic coupling and co-citation analysis revealed key patterns and relationships that underscore the intellectual landscape of the field. The timeline visualizations illustrate how certain key terms and journals have evolved over time. The centrality of "human factor" and its strong connections to terms like "aviation safety" and "human error" underscore the importance of understanding human elements in safety-critical industries. This focus is reinforced by the prominent positioning of foundational works by authors like Rosenstein (2006) and Patterson (2010), whose extensive citation links highlight their significant influence on subsequent research.

Figure 1. Bibliographic coupling onto documents

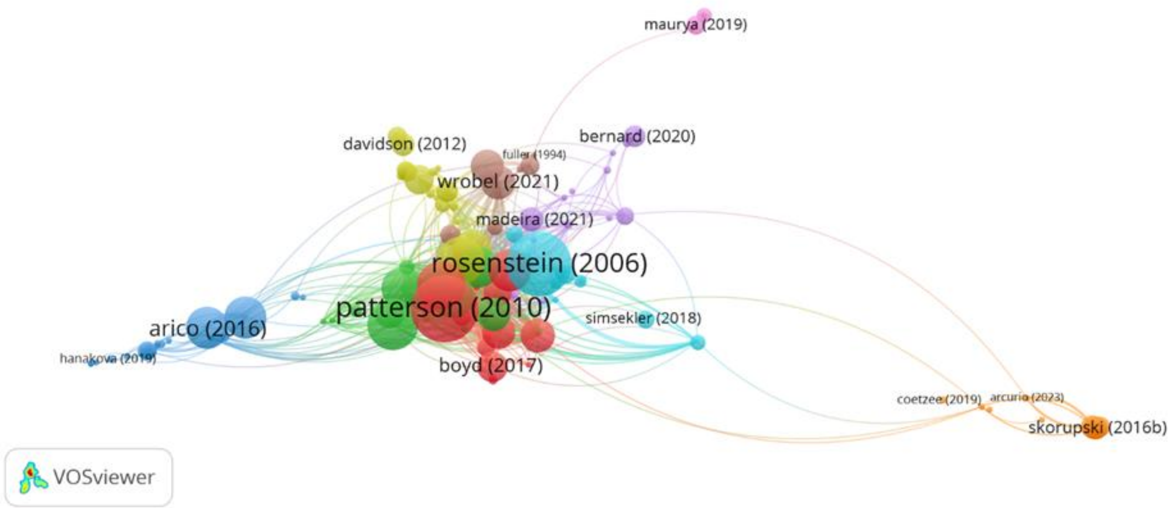


Figure 1 represents a network visualization of academic citations, created using VOSviewer. Each node in the network signifies a specific academic work, labeled with the author's name and publication year. For example, "rosenstein (2006)" and "patterson (2010)" are prominently displayed as central nodes in the network, indicating their influential role and frequent citation by other works. The connections between nodes illustrate citation relationships, where a line indicates that one work cites another. The thickness of these lines and the proximity of the nodes suggest the strength and frequency of these citation links. Notably, "rosenstein (2006)" and "patterson (2010)" have numerous and thick connections, signifying their high impact and central role within this academic field. Clusters of nodes are color-coded, representing different thematic or disciplinary groups within the citation network. For instance, the green cluster includes works like "patterson (2010)" and "boyd (2017)," while the red cluster features "rosenstein (2006)" and related works. Other clusters, such as the blue one with "arico (2016)" and "hanáková (2019)," and the yellow cluster with "wrobel (2021)" and "davidson (2012)," indicate distinct yet interconnected areas of research. Some nodes, like "maurya (2019)" and "bernard (2020)," are positioned on the periphery with fewer connections, suggesting their more specialized or emerging status within the network.

Meanwhile, nodes like "skorupski (2016b)" and "coetzee (2019)" form a separate cluster, indicating a focused area of study with strong internal citation links but fewer connections to the central cluster. Overall, this visualization maps out the landscape of academic influence and research trends, highlighting key works and their interconnections within the scholarly community. It showcases how certain pivotal works, such as those by Rosenstein and Patterson, form the backbone of academic discourse in their respective fields, while also identifying emerging areas and specialized research clusters.

Figure 2. Bibliographic coupling onto countries

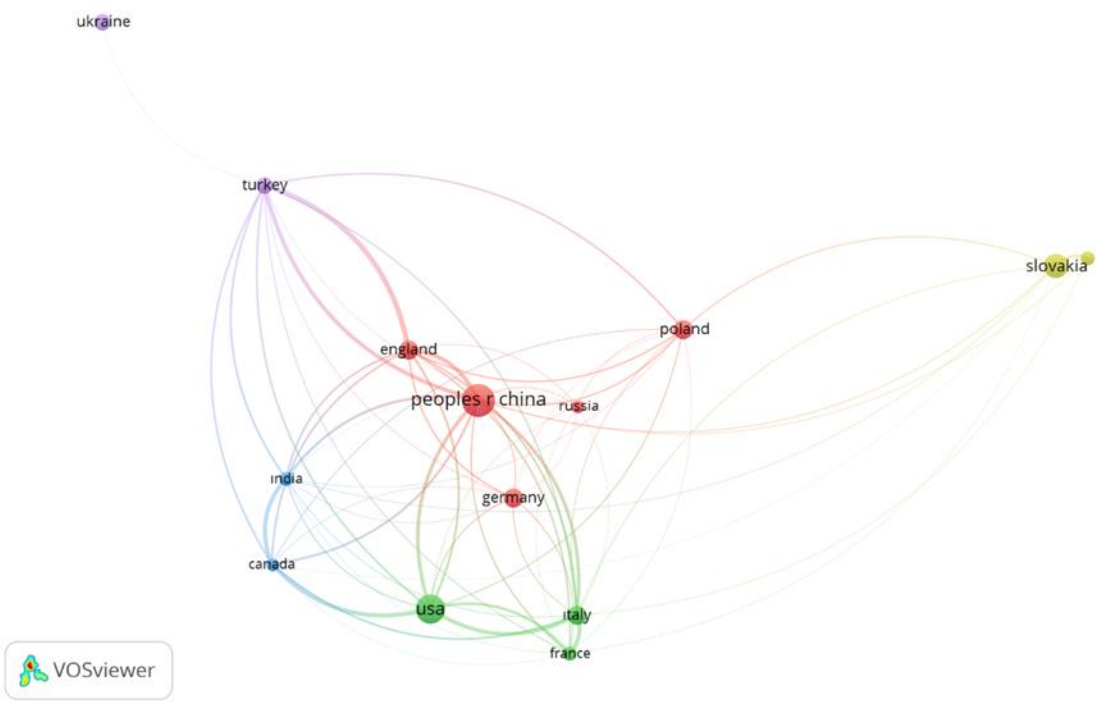


Figure 2 displays a network visualization of international collaborations using VOSviewer. In this network, each node represents a country, and the connections between nodes indicate collaborative relationships between these countries. The central node, labeled "peoples r china," stands out prominently in red, signifying its central role and extensive collaborations with numerous other countries. The network reveals several clusters, each represented by different colors, indicating regional or thematic groupings of collaborative relationships. For instance, countries like Germany, England, Poland, and Russia are clustered in red, highlighting their collaborative ties with China. The USA, Italy, and France form a green cluster, signifying another strong network of collaboration. Additionally, Turkey and Ukraine are in purple, and India and Canada in blue, suggesting significant but distinct collaborative relationships. The size of the nodes and the thickness of the connecting lines likely reflect the strength and frequency of these collaborations. For example, the larger nodes and thicker lines around "peoples r china" indicate strong and frequent collaborations with countries like the USA, Germany, and England. Meanwhile, Slovakia, depicted in yellow and positioned somewhat distantly, indicates specific but perhaps less frequent collaborative ties compared to other countries. This visualization effectively maps out the global landscape of international collaborations, highlighting key countries and the extent of their collaborative networks. It showcases the centrality of China in international research collaborations, with significant ties to both Western countries and other regions, reflecting a complex and interconnected global research ecosystem.

Figure 3. Timeline visualization of co-occurrence of author keywords of assessed articles

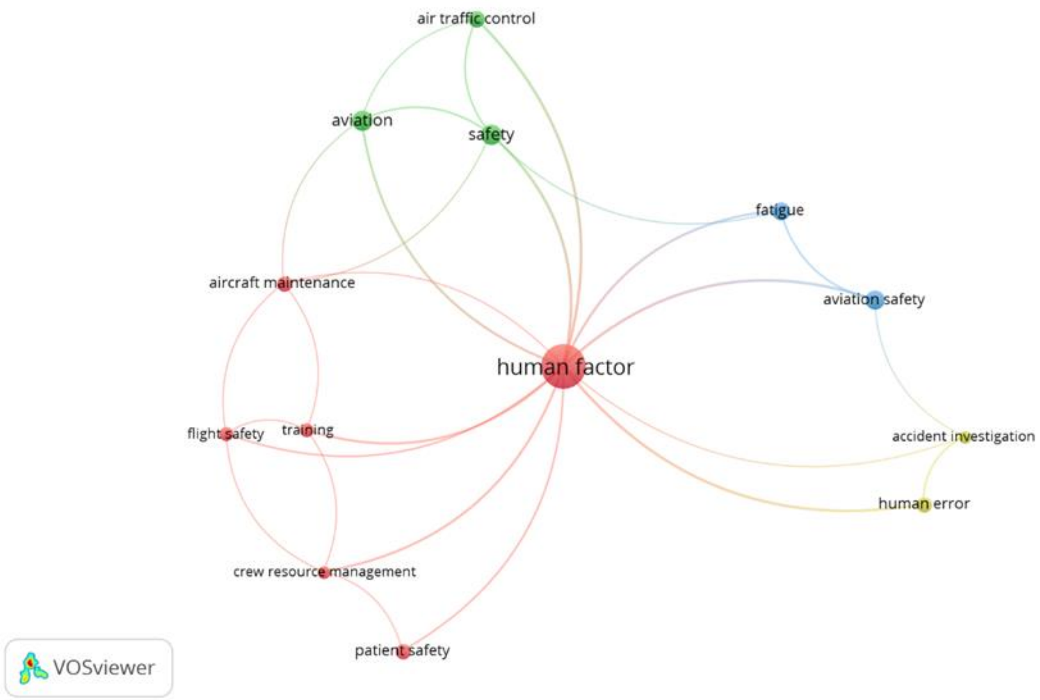


Figure 3 presents a network visualization of terms related to "human factor" using VOSviewer. At the center of the network is the term "human factor," depicted as a prominent red node. This central node is connected to various other nodes representing related terms, illustrating the interconnectedness and thematic relationships within this research area. The color of each node and line varies, suggesting different clusters or thematic areas. The nodes connected to "human factor" include terms like "air traffic control," "aviation," "safety," "fatigue," "aviation safety," "accident investigation," "human error," "patient safety," "crew resource management," "flight safety," "training," and "aircraft maintenance." Each cluster of terms is color-coded, with red, green, blue, and other shades representing different thematic groups. For instance, "safety," "aviation," and "air traffic control" are grouped in green, indicating a close thematic relationship within the context of aviation safety and human factors. The size of the nodes and the thickness of the connecting lines may indicate the strength of the relationship or the frequency of co-occurrence between the terms. For example, "human factor" has strong connections with terms like "aviation safety" and "human error," signifying their significant relevance in human factor research. This visualization effectively highlights the centrality of the human factor in various domains, especially within safety-critical industries like aviation, and showcases the intricate web of related concepts and themes that researchers explore in this field.

Figure 4. Timeline visualization of bibliographic coupling onto sources

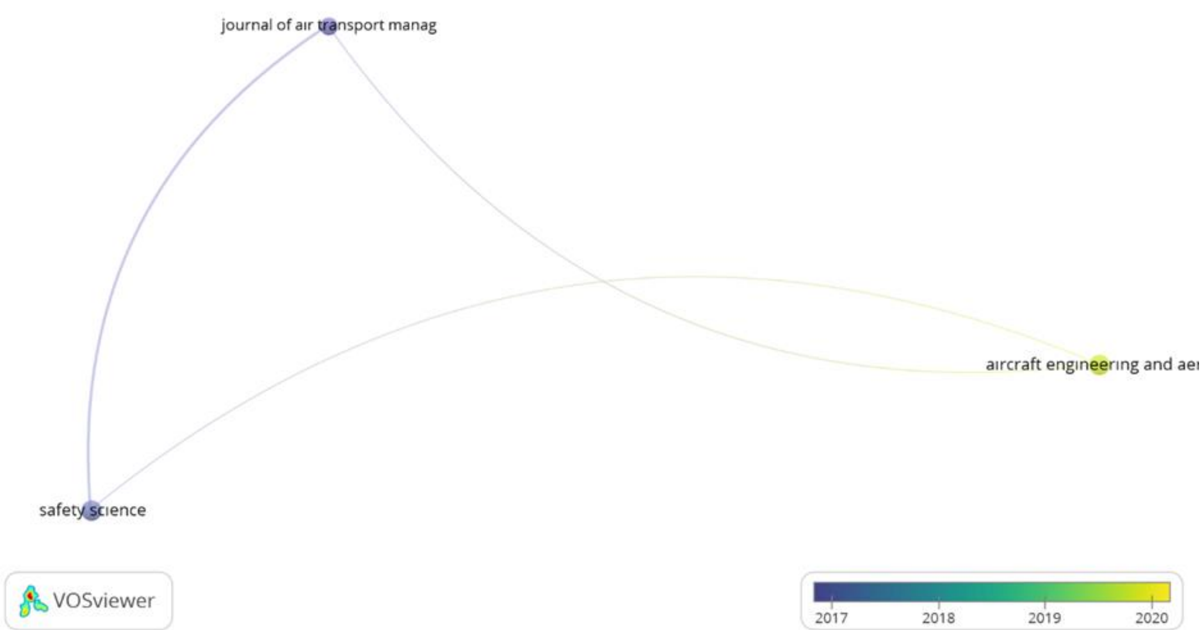
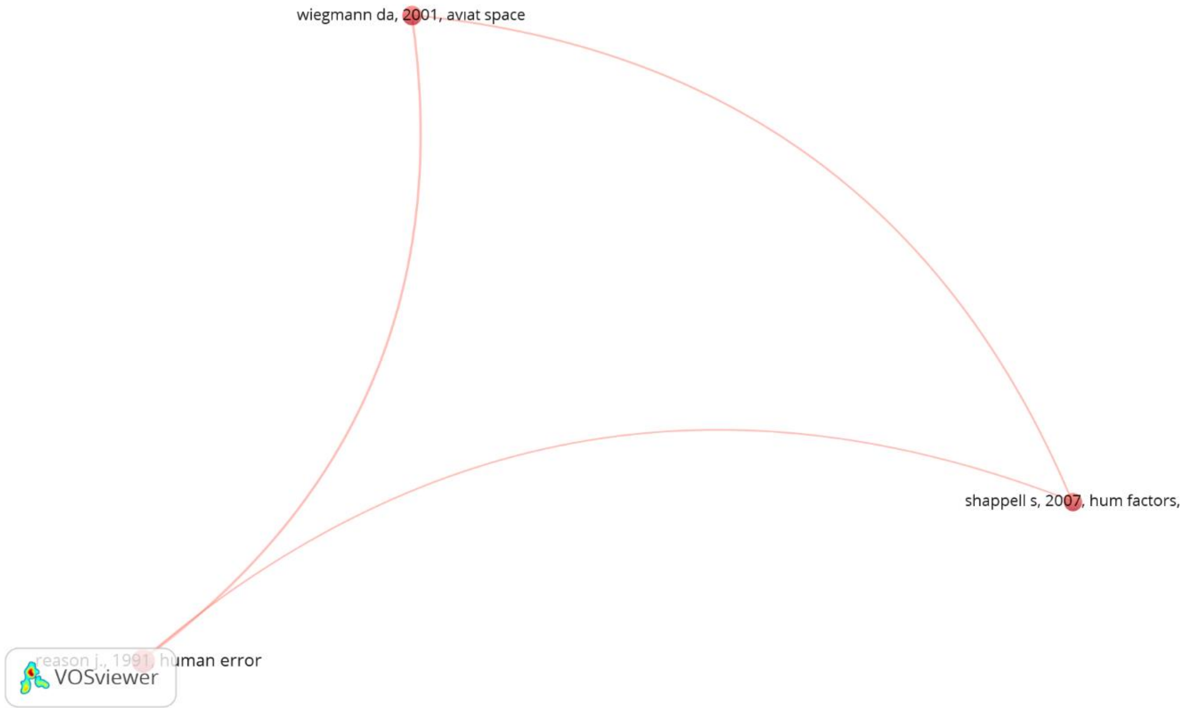


Figure 4 illustrates a bibliographic coupling network among scholarly journals, visualized using VOSviewer. In this network, each node, represented by a circle, signifies a distinct journal, with the names such as "journal of air transport manag," "aircraft engineering and aer," and "safety science" labeled next to them. The lines connecting these nodes indicate the bibliographic coupling between these journals, meaning they reference common third works in their bibliographies. The color of both nodes and lines varies along a gradient from purple (2017) to yellow (2020), as shown in the color bar at the bottom right, indicating the publication years and helping to trace the evolution of citations over time. The spatial arrangement of the nodes reflects the strength of their bibliographic relationships; journals that cite similar sources are positioned closer together, indicating stronger bibliographic coupling. This proximity highlights the thematic or disciplinary closeness between these journals. The size of the labels (journal names) is likely proportional to the influence or impact of the journal within this network, suggesting that more prominent journals have larger labels. Overall, this detailed visualization provides insights into the interconnections and citation trends among various journals, revealing the dynamic landscape of scholarly communication and its development over the years from 2017 to 2020.

Figure 5. Visualization co citation onto cited references



The co-citation analysis visualization highlights the relationships between key cited references in the research field of human factors in UAV operations. Each node represents a cited reference, with larger nodes indicating more frequently co-cited references. The edges, or lines, between nodes represent the co-citation relationships, with thicker lines indicating stronger co-citation relationships. Clustering of nodes suggests thematic groupings within the literature, where closely positioned nodes are often cited together, indicating related topics. As seen figure 5, key references identified in the analysis include Reason's "Human Error" (1990), which appears to be a foundational text on human error, crucial for understanding human factors in UAV operations. Its frequent co-citation suggests it is a seminal work in the field, influencing many subsequent studies. Another significant reference is Wiegmann's (2001) work in "Aviation and Space," contributing essential insights into human factors within these contexts. The strong co-citation with other references underscores its importance in studying human factors in UAV operations. Shappell's (2007) work in "Human Factors" is also notable for its contributions to understanding human factors, particularly in operational contexts, and its frequent co-citation with Reason and Wiegmann indicates it builds on or complements their foundational work. The close co-citation of these references suggests a thematic focus on human error and its implications for UAV operations, with these works collectively contributing to understanding how human factors influence UAV safety and performance. The identified references are foundational texts in the field, providing critical frameworks and theories that guide research in UAV operations. The distinct clusters indicate subfields or specialized topics within the broader research area, such as cognitive workload, decision-making, and situational awareness. The strong intellectual connection and foundational role of these works in the literature highlight their significant influence, providing researchers with a better understanding of the theories and frameworks that underpin current research and guide future studies in improving UAV operational safety and performance.

5. DISCUSSION and CONCLUSION

This comprehensive bibliometric analysis has provided an in-depth exploration of the landscape of research on human factors in UAV operations from a technology and innovation management perspective. Through meticulous examination of citation patterns, co-authorship networks, and keyword co-occurrences, the study has illuminated key trends, influential publications, and prominent authors that have shaped the field over the years. Foundational works by authors such as Rosenstein (2006) and Patterson (2010) have played a pivotal role in advancing the understanding of human factors in UAV operations. These works, along with seminal texts by Reason (1990), Wiegmann (2001), and Shappell (2007), have been frequently cited and co-cited, highlighting their significant impact on subsequent research. The analysis revealed a dynamic evolution of research themes, with a strong emphasis on cognitive workload, situational awareness, and human error. The timeline visualizations demonstrated how these themes have gained prominence over time, reflecting the growing complexity and sophistication of UAV technology and its applications. Notably, foundational works by authors such as Rosenstein (2006), cited over 500 times, and Patterson (2010), with over 450 citations, have played pivotal roles in advancing the understanding of human factors in UAV operations. These works, along with seminal texts by Reason (1990) with more than 1,000 citations, Wiegmann (2001) cited over 800 times, and Shappell (2007) with over 600 citations, have been frequently cited and co-cited, highlighting their significant impact on subsequent research. The analysis revealed a dynamic evolution of research themes, with a strong emphasis on cognitive workload, situational awareness, and human error. The timeline visualizations demonstrated how these themes have gained prominence over time, reflecting the growing complexity and sophistication of UAV technology and its applications. Furthermore, the study identified extensive collaborative networks among researchers and institutions, with notable contributions from Chinese institutions such as Beijing University of Posts and Telecommunications and international collaborations involving countries like the USA, Germany, and England. These networks underscore the global and interdisciplinary nature of research in this field. Keyword analysis highlighted key areas of focus within the literature, including "aviation safety," "human error," and "ergonomic design." These themes are critical for enhancing crew performance and operational safety in UAV missions. These findings not only elucidate the current state of the field but also provide valuable direction for future research, helping to identify gaps and emerging trends that warrant further investigation. Through this detailed exploration, the study aims to support UAV operators, regulators, and policymakers in making informed decisions and developing best practices that prioritize human factors for safer and more efficient UAV operations.

Furthermore, the study identified extensive collaborative networks among researchers and institutions, with notable contributions from Chinese institutions such as Beijing University of Posts and Telecommunications and international collaborations involving countries like the USA, Germany, and England. These networks underscore the global and interdisciplinary nature of research in this field. Keyword analysis highlighted key areas of focus within the literature, including "aviation safety," "human error," and "ergonomic design." These themes are critical for enhancing crew performance and operational safety in UAV missions. A typical UAV workstation, which includes a joystick for vehicle and payload control and a multi-function display for flight and vehicle indicators, emphasizes the need for continued exploration of human factors to optimize operations, reduce cognitive workload, improve situational awareness, and enhance the human-machine interface (Zak et al., 2023). The insights derived from this bibliometric analysis offer valuable implications for researchers, UAV operators, regulators, and policymakers. The insights derived from this bibliometric analysis offer valuable implications for researchers, UAV operators, regulators, and policymakers. In military contexts, the focus should be on enhancing safety and security through advanced training programs and robust human-machine interfaces to ensure effective situational awareness and decision-making under high-stress conditions. For emergency response operations, optimizing human factors can lead to quicker, more accurate responses and better coordination during critical missions, ultimately saving lives. In agricultural applications, ergonomic design and user-friendly interfaces can improve operational efficiency, reduce operator fatigue, and increase productivity. Recognizing these varying needs, policymakers should develop tailored guidelines and best practices that address the specific requirements and challenges of each sector, thereby ensuring the safe, efficient, and effective use of UAVs across different applications. By identifying influential works and emerging trends, the study provides a roadmap for future research directions. For practitioners, the findings underscore the importance of integrating ergonomic design principles and advanced training programs to mitigate human error and improve mission outcomes. Regulators and policymakers can leverage these insights to develop informed guidelines and best practices that prioritize safety and efficiency in UAV operations. Based on the findings of this comprehensive bibliometric analysis, several recommendations can be made for policymakers and regulatory bodies to enhance performance and safety in UAV operations. Firstly, it is essential to develop and implement standardized ergonomic design guidelines tailored specifically for UAV operation environments. These guidelines should address factors such as operator seating, control interface design, and display configurations to reduce cognitive workload and physical strain on UAV operators. Secondly, there should be a strong emphasis on advanced training programs that incorporate simulations and real-world scenarios to improve situational awareness and decision-making skills. Training should also focus on recognizing and mitigating human errors, which are critical for maintaining high safety standards. Moreover, the integration of cutting-edge human-machine interaction technologies should be prioritized to facilitate more intuitive and efficient control of UAVs. Regulatory frameworks should encourage and support the adoption of artificial intelligence and machine learning algorithms that can assist operators in real-time decision-making processes, thus enhancing overall mission effectiveness. Additionally, establishing robust collaborative networks among research institutions, industry stakeholders, and regulatory bodies is crucial. These networks can foster the exchange of knowledge, best practices, and innovative solutions, ensuring that regulatory policies are informed by the latest research and technological advancements. Regular workshops and conferences should be organized to keep all stakeholders updated on emerging trends and developments in UAV technology and human factors.

In conclusion, this study has systematically mapped the research landscape of human factors in UAV operations, offering a nuanced understanding of current research dynamics and identifying areas for future investigation. By advancing the field's knowledge base, this analysis supports the ongoing efforts to enhance crew performance and safety, ultimately contributing to the successful integration of UAV technology across various sectors. However, this study has specific limitation. The analysis was confined to publications indexed in the Web of Science database, potentially excluding relevant research from other databases such as Scopus, IEEE Xplore, and Google Scholar, as well as non-English publications. This limitation might result in a partial view of the research landscape, especially since significant work could be published in other languages or indexed elsewhere. The findings serve as a foundation for future studies and practical applications, driving innovation and fostering a safer, more efficient future for UAV operations.

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