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Air Traffic Controllers' Perspectives on Unmanned Aerial Vehicles Integration into Non-Segregated Airspace

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Abstract

The integration of Unmanned Aerial Vehicles (UAVs) into non-segregated airspace presents both opportunities and challenges for air traffic control (ATC). The aim of the study is to explore the perspectives of air traffic controllers on the current and anticipated challenges, workload, stress factors, performance errors, and mitigation strategies related to UAV integration. The sample consisted of 213 air traffic controllers in Türkiye. UAV operations have been available in Türkiye not only for military purposes but also for purposes such as forest fires, earthquakes, security, and others for a long time, and these UAV operations are provided with air traffic services (ATS) by air traffic controllers. The results show that air traffic controllers are concerned about mid-air collisions due to UAV technology limits and regulatory gaps, along with managing risks and unique flight characteristics. Addressing technology limitations, regulatory ambiguity, and other factors necessitates a comprehensive strategy. Solutions must prioritize collision avoidance systems, clear communication guidelines, and defined no-fly zones. It is recommended that future studies focus on the comprehensive impact of UAVs on air traffic operations and the development of regulations.

1. Introduction

Advances in aviation technology and societal demands have contributed to the growing popularity and increasing use of unmanned aerial vehicles (UAVs), also known as unmanned aircraft systems (UAS) (Cyganczuk, & Roguski, 2023; Shaaban Ali et al., 2022). UAVs present considerable financial benefits in contrast to traditional manned aircraft (Malone et al., 2013). UAVs are extensively utilized in various domains such as health, agriculture, package delivery, disaster management, and surveillance (Bhatt, Pourmand, & Sikka, 2018; Euchi, 2021; Otto et al., 2018; Pathak, Mohod, & Sawant, 2020; Politi et al., 2021; Shah et al., 2020; Sujit, Saripalli, & Sousa, 2014; Thiels et al., 2015). Their rapid rise challenges integrating them harmoniously into traditional aircraft-dominated airspace (Correa et al., 2012; Pop et al., 2017; Shaaban Ali et al., 2022).

The growing popularity of UAVs has the potential to reshape the future of the aviation industry. The operations of UAVs were planned to take place within segregated airspace (Pastor et al., 2014; Simpson, & Stoker, 2006). However, there are significant challenges to integrating UAVs safely and efficiently into non-segregated airspace. There has been a growing necessity for the integration of UAVs into the entire existing airspace and the current air traffic control (ATC) system faces technical challenges in accommodating higher tempo and density for heavy UAV operations (Thipphavong et al., 2018). Emphasized within this integration process is the need for UAVs to access non-segregated airspace and conduct operations within the same environment as traditional aircraft (Grote et al., 2021). The coexistence of mixed traffic, comprising both UAVs and manned aircraft, within the same airspace has the potential to impact various functions of ATC (DeGarmo, 2004).

The integration of UAVs into airspace directly impacts the role and responsibilities of air traffic controllers. It affects ATC by necessitating changes in procedures, automation, and policies concerning flight plans, patterns, communication, and more (Kamienski, & Semanek, 2015). Integrating UAVs can present controllers with different challenges and potentially compromise their performance and aviation safety (Wang et al., 2022). Developing specialized systems to manage UAVs separately from traditional air traffic is essential for ensuring safe integration within non-segregated airspace.

Controllers are responsible for the safe, expeditious, and orderly flow of air traffic in aerodromes and airspaces (Bakare, & Junaidu, 2013; Malakis et al., 2019; Mooji, & Corker, 2002; Pavlinovic, Juricic, & Antulov-Fantulin, 2017). Controllers must ensure that all aircraft, including UAVs, fly safely and without any issues in airspace. This introduces a new and dynamic situation faced by controllers, presenting new challenges in terms of safety, efficiency, and organization. The new systems and technologies may bring challenges by increasing aircraft volume and complexity in designated airspace, necessitating additional requirements in ATC (Miller et al., 2020; Mueller, Kopardekar, & Goodrich, 2017). With the implementation of new technologies, controllers must balance a greater influx of data and information flow while effectively managing their workload. Additionally, the interaction between traditional airspace users and UAVs must be considered, as it can further complicate the controllers' task of ensuring the safe and efficient operation of both sides. Integrating UAVs in a shared airspace poses challenges such as interaction adaptation, controlled information sharing, and continuous monitoring and adaptation (Anisetti et al., 2020), which align with the increased workload and complexities faced by controllers due to the implementation of new technologies (Brookings, Wilson, & Swain, 1996; Debernard, Vanderhaegen, & Millot, 1992; Tattersall, Farmer, & Belyavin, 1991).

A scalable solution for the integration of airspace is important for the operations of commercial UAVs while mitigating the impact on ATC (Ferguson, & McCarthy, 2017). UAV Traffic Management (UTM), as highlighted by Ancel et al. (2017) and Sandor (2017), stands as a traffic management system ensuring the safe and efficient integration of UAVs into airspace. It encompasses frameworks and services designated to manage UAV traffic within the airspace (Chin, Li, & Pant, 2022). UTM mitigates challenges in airspace integration (Mueller, Kopardekar, & Goodrich, 2017) and minimizes associated risks (Cauwels et al., 2020). For the support of unmanned aircraft systems, UTM necessitates the adaptation of existing Air Traffic Management (ATM) regulations, acknowledging the differences between manned and unmanned flight operations, and the integration of Communication, Navigation, and Surveillance (CNS) Technologies (Ali, 2019).

A review of the literature reveals numerous studies on Unmanned Aerial Vehicle (UAV) integration into airspace (Allouche, 2000; Carr, 2013; Dalamagkidis et al., 2008; DeGarmo, 2004; Ho et al., 2019; Lacher et al., 2010; Peterson, 2006; Radmanesh, 2016; Ribeiro et al., 2017). However, a critical gap exists – the limited involvement of air traffic controllers, who are central to airspace management. Despite the study by Kamienski & Semanek (2015) focusing on flight planning and automation, the control link, specific information and procedures, ATC training, and interaction with the future airspace of UAVs, this research was acknowledged as an initial step, highlighting the need for further studies. Given the rapid advancements in UAV technology and their increasing use in airspace today, there is a need for a comprehensive study focusing on air traffic controllers, which would bridge the gap in the existing literature and provide guidance for future studies on UAV integration into airspace. This study aims to examine how UAVs, with their new technology and performance, are integrated into non-segregated airspace from the perspective of controllers, compared to traditional aircraft. It discusses the experiences, challenges, technical barriers, regulations, and human factors faced by controllers. Additionally, it presents solutions to ensure flight safety, effectiveness, and operational efficiency during this integration process. The aim is to understand the significant changes in the aviation industry and develop effective strategies to overcome emerging challenges. Integrating UAVs into non-segregated airspace shapes the future of aviation, and this research aims to aid in comprehending and managing this transformation from the viewpoint of air traffic controllers, important figures in the aviation sector.

2. Literature Review

Integrating UAVs into non-segregated airspace poses complex challenges for ATC operations. Defining the correlation between UAVs and ATC and understanding potential issues is crucial (Baum et al., 2019; Neto et al., 2022). Addressing these challenges is critical to ensure safe and efficient operations in non-segregated airspace. Specific issues faced by controllers in UAV integration are identified through a literature review.

2.1. Collision Avoidance Capability

The systems such as Traffic Alert and Collision Avoidance System (TCAS) and Ground Proximity Warning System (GPWS) are used to prevent collisions between aircraft or with obstacles in traditional aviation. The current UAV technology has been developed to improve flight safety by providing visual data to remote UAV pilots at ground stations (Karthick, & Aravind, 2010). However, collision avoidance systems and protocols should be developed, especially for smaller UAV models, to prevent accidents in increasingly congested airspace. Collision avoidance systems are emerging as a major focus of recent research on UAVs (Shan et al., 2023). Collision avoidance systems should be used to enable UAVs to continue their operations safely and efficiently in urban and other airspaces alongside traditional air traffic (Barfield, 2000; Van der Veeken et al., 2021).

2.2. Different Operating Characteristics

UAVs differ significantly from manned aircraft. UAVs can cruise at different speeds, fly at varying altitudes, and exhibit a variety of maneuvering capabilities. The integration of these diversities into controlled airspace requires extremely precise planning (Albaker, & Rahim, 2011; Jack, & Hoffler, 2014; Kamienski, & Semanek, 2015; Valavanis, & Vachtsevanos, 2015; Wilson, 2018). This is because detailed planning and coordination are required to manage and use these variable characteristics in a compatible manner. A strategic approach is required to safely and efficiently control the dynamics that are quite different from manned aircraft in separation and contingency management (Pastor et al., 2014).

2.3. Technology Limitations & Limited Detectability

In traditional air traffic, the detection of aircraft in controlled airspace using radar is important for air space management. Different equipment is available on traditional aircraft for this detection. However, the detection of UAVs flying at low altitudes close to the ground, especially with their small and complex shapes, can be difficult for traditional radar systems (Hasan, Pandey, & Raj, 2022; Khawaja et al., 2022; Shao, Zhu, & Li, 2022; Song et al., 2019). This situation requires the use of alternative technologies in ATC systems (DeGarmo, 2004).

2.4. Regulatory Framework

Traditional aviation rules are not applicable to UAVs because they have different technical characteristics from manned aircraft (Sandor, 2019). This requires the development of new regulations for UAVs, which are still under development, and their harmonization at the international level. The different functional features of UAVs necessitate a separate approach from traditional methods in aviation safety regulations (Arblaster, 2018; Vidović et al., 2019). It is a serious challenge to define clear rules and regulations for the integration of UAVs into the existing air traffic without disrupting it (Huttunen, 2019; Stöcker et al., 2017).

2.5. Communication

Communication between UAVs and ATC systems presents challenges, such as different flight profiles, wider bandwidth ranges, and different ground station characteristics compared to manned aircraft (Matolak, 2015). Communication between UAVs and ATC systems is generally established through UAV ground control stations (GCS). These GCS can be simple commercial products like tablets or radio control stations, or more advanced technologies like portable, fixed, or self-propelled technologies (Vasile et al., 2019). It is essential for communication, flight control, and ensuring safe and secure operations (Dianovsky, Pecho, & Bugaj, 2023). Effective communication between UAVs and air traffic controllers is critical for airspace integration (Stansbury, Vyas, & Wilson, 2009). The current communication networks of UAVs are typically based on point-to-point communication with limited range, unlike manned aircraft (Bauranov, & Rakas, 2021). Two-way data communication between UAVs and ATC supported by automation can provide more efficient and safer integration (Geister, & Geister, 2013; Gunawardana, & Alonso, 2013; Kim, Jo, & Shaw, 2015; Koeners et al., 2006; Paczan, Cooper, & Zakrzewski, 2012; Ponchak et al., 2018; Swieringa et al., 2019). Additionally, there is potential for UAVs to create complexity and impact airspace efficiency, especially in the communication dimension, when integrated with traditional air traffic (Truitt, Zingale, & Konkel, 2016).

2.6. Risk Management

To ensure the efficient integration of UAVs into uncontrolled airspace, all safety-related challenges must be addressed (Simpson, & Stoker, 2006). Integration of UAVs into the airspace brings along challenges such as risks, threats, and potential illegal use (Pop et al., 2017). The current air traffic management has not yet reached the point of mitigating all risks associated with UAV operations (Vidovic et al., 2019). Therefore, the increasing use of UAVs in the airspace requires comprehensive risk management that not only identifies but also manages and mitigates these risks (Başak, & Gülen, 2008; Davies et al., 2021; Kobaszynska-Twardowska, Łukasiewicz, & Sielicki, 2022; Naji, & Ayari, 2023).

2.7. Security/Safety Concerns & Geofencing and No-Fly Zones

UAV operations must be conducted in accordance with the existing regulations (Kakarla, & Ampatzidis, 2018). However, UAV users who do not have sufficient knowledge of the airspace or the relevant regulations may cause serious flight safety problems by flying over restricted or prohibited airspace, such as airports (Moreira, Papp, & Ventura, 2019). Geofencing technology can be used to prevent UAVs from entering restricted or prohibited airspace by creating no-fly zones or defining areas where only flying is allowed (Yılmaz, & Ulvi, 2022). Geofences, which define virtual boundaries in a specific geographic area, can effectively organize the airspace and provide solutions to security concerns (Dasu, Kanza, & Srivastava, 2018; Hosseinzadeh, 2021; Stevens, & Atkins, 2020; Zhu, & Wei, 2016).

2.8. Training

Air traffic controllers must be adequately trained to ensure the efficient integration of UAVs into the airspace. Controllers need to understand the unique aspects of UAV operations compared to manned aircraft (Kamienski et al., 2010; Valavanis, & Vachtsevanos, 2015). National and international standards and practices should be used to update air traffic controller training programs to cover UAV-specific topics such as link and communication loss, and performance (Kamienski, & Semanek, 2015). The training process helps controllers to change their negative perceptions of UAVs, which may be caused by uncertainty, and to become more familiar with UAV operations (Truitt, Zingale, & Konkel, 2016).

2.9. Workload & Stress

The increasing number of both manned and UAVs presents significant challenges for air traffic controllers. Non-compliance with traditional air traffic standards significantly increases the workload for controllers dealing with UAV operations (Truitt, Zingale, & Konkel, 2016). Furthermore, the coordination, communication, and management of UAVs within the non-segregated airspace add to the complexity of ATC, requiring additional effort from controllers (Al-Mousa et al., 2019). The distinctive characteristics of UAVs, such as their varied speeds and altitudes, further contribute to this complexity and can lead to increased stress and additional responsibilities for controllers (Brookings et al., 1996). The innovative technology of UAVs also brings technological changes and procedures to ATC systems, which can be a source of stress (Finkelman, & Kirschner, 1980; Liu, Feng, & Zeng, 2019; Tomic, & Liu, 2017). Additionally, factors such as limited controllability of UAVs, uncertainty, increasing number of controlled traffic and changing nature of traffic, and high responsibility can also be sources of stress (Costa, 2000; Tattersall, Farmer, & Belyavin, 1991; Zeier, Brauchli, & Joller-jemelka, 1996; Zhang et al., 2023). To ensure a balanced workload and manageable stress levels while maintaining safe and efficient air traffic management, the gradual integration of UAVs into the airspace must be carefully considered, considering the working conditions of air traffic controllers (Baum et al., 2019).

3. Methodology

The study aims to answer the following research question: "What are the perspectives of air traffic controllers regarding the present and anticipated challenges, workload, stress factors, performance errors, and mitigation strategies concerning UAV integration? Furthermore, how do these perspectives differ between air traffic controllers who provide ATS (Air Traffic Services) and those who do not provide ATS?".

This study employs a mixed-methods approach to investigate the integration of UAVs into non-segregated airspace. The study combines a comprehensive literature review with a survey of experienced air traffic controllers.

Surveys, functioning as standardized data collection tools for large samples within short timeframes, encompass four distinct question types - factual, knowledge, behavioral, and attitudinal - tailored to the measured property (Balcı, 2012; Büyüköztürk, 2005).

A comprehensive review of the literature and expert consultations were conducted to define five key categories for evaluating the integration of UAVs into non-segregated airspace. These categories are specific challenges, workload, stress, performance errors, and mitigation strategies. The details of these categories and their sub-categories are shown in Table 1.

The sample of the study consisted of 213 air traffic controllers in Türkiye. At the time of the study, there were 2035 active air traffic controllers in Türkiye. The sample size of the study (n>200) was considered sufficient for this known population (n>1000) with a 95% confidence level and a +/-5% margin of error (Krejcie, & Morgan, 1970; Yamane, 1967). The survey was conducted online. The questionnaire included items prepared on a 5-point Likert scale related to the categories and subcategories shown in Table 1, along with demographic variables. The survey was based on the voluntary participation of the participants, and all survey responses were processed anonymously. Table 2 shows the demographic characteristics of the survey participants.

Table 1. Key areas for evaluating UAV integration into non-segregated airspace

Challenges	(1) Collision Avoidance Capability; (2) Different Operating Characteristics; (3) Technology Limitations & Limited Detectability; (4) Regulatory Framework; (5) Communication; (6) Risk Management; (7) Security Concerns; (8) Training
Workload Factors	(1) Increased Traffic Volume; (2) Diverse Operating Characteristics; (3) Complexity in Integration; (4) Monitoring and Surveillance; (5) Regulatory Compliance; (6) Adaptation to New Technologies; (7) Emergency Response and Contingencies; (8) Workforce Capacity
Stress Factors	(1) Increased Workload; (2) Complexity and Uncertainty; (3) Continuous Monitoring; (4) Safety Concerns; (5) Regulatory Challenges; (6) Communication Complexity
Performance Errors	(1) Misidentification or Loss of Separation; (2) Communication Errors; (3) Procedural Errors; (4) Inattention or Overload Errors; (5) Decision-making Errors; (6) Technology-related Errors
Mitigation Strategies	(1) Geofencing and No-Fly Zones; (2) UAV Traffic Management (UTM); (3) Regulatory Framework Updates; (4) Collision Avoidance Systems; (5) Enhanced Communication Protocols; (6) Training Programs; (7) Public Awareness Campaigns; (8) Risk Assessment and Management

Table 2. Socio-demographic profile

		n	%
Sex	Female	70	32.9
	Male	143	67.1
Unit	Aerodrome Control Unit (TWR)	101	47.4
	Approach Control Unit (APP)	62	29.1
	Area Control Centre (ACC)	50	23.5
Degree	Bachelor's degree	166	77.9
	Graduate Studies	47	22.1
Experience	0-5 years	35	16.4
	6-10 years	34	16.0
	11-20 years	86	40.4
	> 20 years	58	27.2
Air Traffic Service (ATS)	ATS-providing	171	80.3
	non-ATS-providing	42	19.7
Total		**213**	**100.0**

The data collected from the participants was analyzed using IBM SPSS V 26. Descriptive statistics, such as mean scores, standard errors, and standard deviations, were employed to understand the responses comprehensively. An analysis of the differences between the perceptions of challenges, workload factors, stress factors, performance errors, and mitigation strategies by the ATS-providing and non-ATS-providing groups was conducted using independent samples t-tests. The normality assumption for the t-test was met in the study, with the condition of n>30 being fulfilled (Orhunbilge, 2000).

4. Findings

Table 3 shows the mean scores, standard errors, standard deviations, and normality of survey responses from air traffic controllers regarding the challenges, workload, stress, performance errors, and mitigation associated with integrating UAVs into non-segregated airspace. The data utilizes a 5-point Likert scale format for mean scores, where higher scores indicate a greater perception of these issues.

4.1. Challenges

According to the analysis results of challenges in the integration of UAVs into controlled airspace shown in Table 3, the mean score varies between 3.89 and 4.59 on a 5-point Likert scale. This indicates that air traffic controllers perceive these challenges as a significant concern. Additionally, the standard deviations for all challenges are relatively low, indicating a high level of agreement among the controllers on the relative importance of these issues.

Collision avoidance capability and regulatory framework topped the list with mean scores of 4.51 and 4.59 respectively. This highlights the controllers' concerns about potential mid-air collisions due to limitations in UAV technology and the lack of established regulations governing safe UAV integration. Following closely behind are risk management and different operating characteristics with mean scores of 4.49 and 4.46 respectively. These concerns highlight the perceived challenge of managing potential risks associated with UAVs as well as the challenges posed by their unique flight characteristics compared to manned aircraft. Communication emerges as a significant concern, receiving a mean score of 4.44, indicating significant concern about maintaining effective communication channels with UAVs, particularly in situations where traditional methods may prove inadequate. Technology limitations and limited detectability received a mean score of 4.37, indicating concerns about the reliability of UAV technology and the potential for them to be difficult to detect on radar. Security concerns also received a significant mean score of 4.28, emphasizing concerns regarding the potential misuse of UAVs for unauthorized purposes. Interestingly, training received the lowest mean score, at 3.89, suggesting that controllers might feel somewhat more confident in their ability to address this challenge through additional training compared to the others.

Differences in challenges between the ATS-providing and non-ATS-providing groups are shown in Table 4. There are differences in technology limitations & limited detectability, communication, risk management, security concerns, and training. In the ATS-providing group, averages range from 3.77 (Training) to 4.57 (Regulatory Framework), while in the non-ATS-providing group, averages range from 4.40 (Training) to 4.74 (Communication). Both groups perceive training as the least challenging aspect, albeit with a slightly lower mean score in the ATS-providing group. In contrast to the non-ATS-providing group's view of communication as the primary challenge, the ATS-providing group identifies regulatory framework as the predominant difficulty, similar to the overall perception.

Table 3. Mean, Std. error, Std. deviation, and Normality of results

	Mean	Std. Error	Std. Deviation	Skewness	Kurtosis
Challenges (CH)					
Regulatory Framework	4.59	.044	.642	-1.317	.542
Collision Avoidance Capability	4.51	.048	.705	-1.349	1.288
Risk Management	4.49	.044	.649	-.898	-.281
Different Operating Characteristics	4.46	.045	.662	-.837	-.408
Communication	4.44	.052	.754	-1.117	.372
Technology Limitations & Limited Detectability	4.37	.056	.811	-1.032	.113
Security Concerns	4.28	.057	.833	-1.113	.997
Training	3.89	.076	1.104	-.845	.154
Workload Factors					
Diverse Operating Characteristics	4.47	.046	.670	-1.077	.759
Complexity in Integration	4.45	.044	.640	-.742	-.463
Emergency Response and Contingencies	4.45	.049	.710	-1.064	.384
Increased Traffic Volume	4.37	.049	.713	-.680	-.772
Monitoring and Surveillance	4.29	.059	.863	-1.090	.642
Workforce Capacity	4.29	.057	.830	-.889	-.130
Regulatory Compliance	4.15	.059	.859	-.781	.141
Adaptation to New Technologies	3.99	.059	.863	-.604	-.012
Stress Factors					
Complexity and Uncertainty	4.69	.037	.537	-1.566	1.550
Safety Concerns	4.61	.042	.610	-1.293	.604
Increased Workload	4.54	.041	.602	-.959	-.078
Continuous Monitoring	4.52	.044	.648	-1.127	.593
Communication Complexity	4.46	.048	.703	-1.170	.933
Regulatory Challenges	4.21	.054	.788	-.569	-.638
Performance Errors					
Communication Errors	4.37	.050	.726	-.849	-.073
Misidentification or Loss of Separation	4.26	.052	.763	-.613	-.605
Procedural Errors	4.21	.055	.799	-.735	.176
Inattention or Overload Errors	4.19	.057	.833	-.869	.698
Decision-making Errors	4.15	.057	.833	-.733	.153
Technology-related Errors	3.91	.061	.885	-.515	.174
Mitigation Strategies					
Enhanced Communication Protocols	4.57	.044	.637	-1.214	.332
Collision Avoidance Systems	4.53	.048	.697	-1.164	-.007
Geofencing and No-Fly Zones	4.44	.048	.695	-.850	-.509
Regulatory Framework Updates	4.35	.052	.754	-.818	-.317
UAV Traffic Management (UTM)	4.34	.048	.700	-.589	-.804
Training Programs	4.32	.054	.784	-.926	.474
Risk Assessment and Management	4.29	.057	.829	-.678	-.914
Public Awareness Campaigns	4.07	.069	1.000	-.800	-.120

Table 4. t-test results of challenges by ATS

	Group	n	Mean	Std. Deviation	t	Sig.
Collision Avoidance Capability	ATS-providing	171	4.49	.706	-.857	.393
	non-ATS-providing	42	4.60	.701		
Different Operating Characteristics	ATS-providing	171	4.42	.676	-1.910	.060
	non-ATS-providing	42	4.62	.582		
Technology Limitations & Limited Detectability	ATS-providing	171	4.30	.832	-2.882	.005*
	non-ATS-providing	42	4.64	.656		
Regulatory Framework	ATS-providing	171	4.57	.660	-1.227	.224
	non-ATS-providing	42	4.69	.563		
Communication	ATS-providing	171	4.36	.780	-3.648	.000*
	non-ATS-providing	42	4.74	.544		
Risk Management	ATS-providing	171	4.43	.677	-3.217	.002*
	non-ATS-providing	42	4.71	.457		
Security Concerns	ATS-providing	171	4.18	.850	-4.785	.000*
	non-ATS-providing	42	4.71	.596		
Training	ATS-providing	171	3.77	1.134	-4.240	.000*
	non-ATS-providing	42	4.40	.798		

*p<0.05

4.2. Workload Factors

According to the analysis results of workload in the integration of UAVs into controlled airspace shown in Table 3, the mean score varies between 3.99 and 4.47 on a 5-point Likert scale. This indicates that air traffic controllers perceive all these factors as posing a workload. Additionally, the low standard deviations for all workload factors (ranging from 0.640 to 0.863) signify a significant level of consensus among air traffic controllers regarding the integration process.

The factors with the highest mean scores are diverse operating characteristics, complexity in integration, and emergency response and contingencies. These mean scores indicate that controllers are most concerned about the variety of UAV capabilities, the complex nature of integrating them into existing airspace, and managing emergencies involving UAVs. While increased traffic volume scores relatively high, its mean score is slightly lower than the aforementioned concerns. This suggests that increased traffic due to UAVs is a concern, but not the most pressing issue compared to the complexities of UAV operation itself. Similarly, monitoring and surveillance reflect a moderate concern, highlighting the need for robust systems to track and manage UAVs effectively. The data indicates that controllers are moderately concerned about workforce capacity and adaptation to new technologies.

Differences in workload factors between the ATS-providing and non-ATS-providing groups are shown in Table 5. There are differences in monitoring and surveillance, adaptation to new technologies, and emergency response and contingencies. In the ATS-providing group, averages range from 3.89 (Adaptation to New Technologies) to 4.45 (Diverse Operating Characteristics), while in the non-ATS-providing group, averages range from 4.36 (Increased Traffic Volume, Regulatory Compliance) to 4.67 (Emergency Response and Contingencies). The reason for adaptation to new technologies being perceived as having a lower workload in the ATS-providing group may be attributed to the fact that there has not been a significant change in the integration of UAVs with ATC systems, and the existing systems can still be used for surveillance and communication purposes.

Table 5. t-test results of workload by ATS

	Group	n	Mean	Std. Deviation	t	Sig.
Increased Traffic Volume	ATS-providing	171	4.37	.695	.139	.889
	non-ATS-providing	42	4.36	.791		
Diverse Operating Characteristics	ATS-providing	171	4.45	.687	-.843	.400
	non-ATS-providing	42	4.55	.593		
Complexity in Integration	ATS-providing	171	4.41	.648	-1.916	.057
	non-ATS-providing	42	4.62	.582		
Monitoring and Surveillance	ATS-providing	171	4.23	.895	-2.168	.031*
	non-ATS-providing	42	4.55	.670		
Regulatory Compliance	ATS-providing	171	4.09	.889	-1.791	.075
	non-ATS-providing	42	4.36	.692		
Adaptation to New Technologies	ATS-providing	171	3.89	.888	-3.348	.001*
	non-ATS-providing	42	4.38	.623		
Emergency Response and Contingencies	ATS-providing	171	4.40	.739	-2.720	.008*
	non-ATS-providing	42	4.67	.526		
Workforce Capacity	ATS-providing	171	4.25	.846	-1.620	.107
	non-ATS-providing	42	4.48	.740		

*p<0.05

4.3. Stress Factors

According to the analysis results of stress factors in the integration of UAVs into controlled airspace shown in Table 3, the mean score varies between 4.21 and 4.69 on a 5-point Likert scale. This indicates that the integration of UAVs is a significant source of stress for controllers. Additionally, the relatively low standard deviations for most factors (ranging from 0.537 to 0.788) indicate a significant level of consensus among controllers regarding these stressors.

The factors with the highest mean scores are complexity and uncertainty, with both exceeding 4.6. This indicates that controllers experience the most stress regarding the complex nature of managing UAVs within existing airspace and potential safety risks associated with their presence. Increased workload and continuous monitoring also score highly, suggesting that the additional workload and constant vigilance required for UAVs significantly contribute to ATC stress. Communication complexities are also identified as stressors, highlighting the challenges of coordinating with diverse UAVs and ensuring effective mitigation strategies in case of emergencies. Interestingly, regulatory challenges score the lowest, with a mean below 4.3, suggesting that while regulations present some challenges, they are a less prominent source of stress compared to the operational complexities of UAV integration.

Differences in stress factors between the ATS-providing and non-ATS-providing groups are shown in Table 6. Statistical differences were found among safety concerns, regulatory challenges, and communication complexities. The average scores for the ATS-providing group range from 4.16 (Regulatory Challenges) to 4.68 (Complexity and Uncertainty), whereas the non-ATS-providing group's averages range from 4.43 (Regulatory Challenges) to 4.88 (Safety Concerns). It is considered that the higher average scores of the non-ATS-providing group are due to less knowledge and lack of experience regarding the subject.

4.4. Performance Errors

According to the analysis results of performance errors in the integration of UAVs into controlled airspace shown in Table 3, the mean score varies between 3.91 and 4.37 on a 5-point Likert scale. This indicates a moderate level of concern for all error factors. Additionally, the standard deviations (ranging from 0.726 to 0.885) indicate some difference in the level of concern among controllers.

Communication errors and misidentification or loss of separation emerge as the error types with the highest mean scores. This indicates that controllers are most concerned about breakdowns in communication with UAV and the potential for losing track of or maintaining safe separation between UAVs and manned aircraft. Procedural errors and inattention/overload errors also score relatively high. This highlight concerns regarding adapting existing procedures to accommodate UAVs and the potential for cognitive overload due to the increased complexity of managing a more diverse airspace. Decision-making errors also appear as a moderate concern. Interestingly, technology-related errors score the lowest. This could imply that controllers have greater confidence in the reliability of technology compared to human factors like communication and decision-making. However, it is crucial to remember that even with reliable technology, human interaction points can still introduce errors.

The differences in performance errors between ATS-providing and non- ATS-providing groups are shown in Table 7. Statistical differences were found among misidentification or loss of separation, communication errors, decision-making errors, and technology-related errors factors between these two groups. The non- ATS-providing group has a higher average. A significant difference was observed in technology-related errors. ATS-providing group perceived technology-related errors as a less significant threat, with a score of 3.83. In contrast, non- ATS-providing group scored technology-related errors higher, with a score of 4.21. This indicates that those with experience in UAV integration may have greater confidence in technology's reliability.

Table 6. t-test results of stress factors by ATS

	Group	n	Mean	Std. Deviation	t	Sig.
Increased Workload	ATS-providing	171	4.52	.607	-1.182	.239
	non-ATS-providing	42	4.64	.577		
Complexity and Uncertainty	ATS-providing	171	4.68	.547	-.582	.561
	non-ATS-providing	42	4.74	.497		
Continuous Monitoring	ATS-providing	171	4.50	.672	-1.248	.216
	non-ATS-providing	42	4.62	.539		
Safety Concerns	ATS-providing	171	4.54	.644	-4.858	.000*
	non-ATS-providing	42	4.88	.328		
Regulatory Challenges	ATS-providing	171	4.16	.807	-2.010	.046*
	non-ATS-providing	42	4.43	.668		
Communication Complexity	ATS-providing	171	4.39	.739	-3.895	.000*
	non-ATS-providing	42	4.74	.445		

*p<0.05

Table 7. t-test results of performance errors by ATS

	Group	n	Mean	Std. Deviation	t	Sig.
Misidentification or Loss of Separation	ATS-providing	171	4.20	.779	-2.505	.013*
	non-ATS-providing	42	4.52	.634		
Communication Errors	ATS-providing	171	4.30	.744	-3.206	.002*
	non-ATS-providing	42	4.64	.577		
Procedural Errors	ATS-providing	171	4.16	.817	-1.759	.080
	non-ATS-providing	42	4.40	.701		
Inattention or Overload Errors	ATS-providing	171	4.14	.856	-1.854	.065
	non-ATS-providing	42	4.40	.701		
Decision-making Errors	ATS-providing	171	4.09	.867	-2.230	.027*
	non-ATS-providing	42	4.40	.627		
Technology-related Errors	ATS-providing	171	3.83	.914	-3.038	.003*
	non-ATS-providing	42	4.21	.682		

*p<0.05

4.5. Mitigation Strategies

According to the analysis results of mitigation strategies in the integration of UAVs into controlled airspace shown in Table 3, the mean score varies between 4.07 and 4.57 on a 5-point Likert scale. This indicates a high level of importance for all strategies in addressing the challenges of UAV integration. Additionally, the standard deviations for mitigation strategies range from 0.637 to 1, indicating a considerable degree of consensus among controllers on the importance of these approaches.

The factors with the highest mean scores are enhanced communication protocols, collision avoidance systems, and geofencing and no-fly zones. This suggests that controllers prioritize clear communication protocols, robust collision avoidance systems, and well-defined restricted airspace zones to mitigate safety risks and ensure efficient traffic management. Both collision avoidance systems and UTM score highly, highlighting the importance of technological advancements in managing UAV traffic. Regulatory framework updates and training programs also receive relatively high scores, emphasizing the need for updated regulations and comprehensive training programs to prepare for controllers. Risk assessment and management scores moderately high, indicating a focus on proactive risk mitigation strategies. Public awareness campaigns score the lowest, suggesting that controllers might perceive them as less critical compared to other strategies.

Table 8 shows the t-test results comparing the perceived importance of mitigation strategies for UAV integration between ATS-providing and non- ATS-providing groups. The analysis reveals no statistically significant differences for all strategies between the ATS-providing and non-ATS-providing groups. This suggests that regardless of prior exposure to the strategy, ATCs perceive their importance similarly.

Table 8. t-test results of mitigation strategies by ATS

	Group	n	Mean	Std. Deviation	t	Sig.
Geofencing and No-Fly Zones	ATS-providing	171	4.43	.694	-.362	.718
	non-ATS-providing	42	4.48	.707		
UAV Traffic Management (UTM)	ATS-providing	171	4.35	.673	.306	.761
	non-ATS-providing	42	4.31	.811		
Regulatory Framework Updates	ATS-providing	171	4.38	.753	1.094	.275
	non-ATS-providing	42	4.24	.759		
Collision Avoidance Systems	ATS-providing	171	4.55	.687	.810	.419
	non-ATS-providing	42	4.45	.739		
Enhanced Communication Protocols	ATS-providing	171	4.59	.629	.825	.410
	non-ATS-providing	42	4.50	.672		
Training Programs	ATS-providing	171	4.28	.799	-1.452	.148
	non-ATS-providing	42	4.48	.707		
Public Awareness Campaigns	ATS-providing	171	4.06	1.030	-.179	.858
	non-ATS-providing	42	4.10	.878		
Risk Assessment and Management	ATS-providing	171	4.26	.844	-.825	.410
	non-ATS-providing	42	4.38	.764		

5. Discussions

A prominent concern is the potential for mid-air collisions due to limitations in UAV technology and the lack of established regulations. Controllers also expressed concerns about managing UAV-related risks and their unique flight characteristics compared to manned aircraft, challenges that were highlighted in previous studies (Colgren, & Holly, 2009). Communication emerged as another concern, highlighting potential difficulties in maintaining reliable communication channels with UAV. Interestingly, training received the lowest mean score. While still a concern, this suggests that controllers might feel somewhat more confident in their ability to address this challenge through additional training compared to the other topics. These findings emphasize the urgency for advancements in UAV technology, the development of a comprehensive regulatory framework, and the establishment of robust risk management strategies. One of the most notable differences between ATS-providing and non-ATS-providing groups is the perceived difficulty of the regulatory framework. The non-ATS-providing group emphasized regulatory compliance to a greater extent, while the ATS-providing group considered it to be of lesser priority. This may be due to the ATS-providing group's greater familiarity with existing ATC systems and their belief that these systems can be adapted to accommodate UAVs.

The analysis also identified workload factors associated with UAV integration. Controllers expressed the most concern regarding diverse operating characteristics, complexity of integration, and emergency response procedures for UAVs. These concerns highlight the need for adaptations in existing ATC procedures and training programs to address the unique challenges posed by UAVs. In terms of workload factors, the ATS-providing group had lower concerns about adapting to new technologies compared to the non-ATS-providing group. While integrating new concepts into the ATC system, particularly those impacting the controller human-machine interface, is a challenge (Ellejmi et al., 2015; Miller et al.,2020), the ATS-providing group is aware of these difficulties but believes that existing ATC systems can be successfully adapted for this task.

Furthermore, the study showed that UAV integration is a significant source of stress for air traffic controllers. The complexity and uncertainty, and safety concerns scored the highest. Controllers typically employ strategies to manage complexity and uncertainty (Corver, & Grote, 2016) because it is well-known that complexity and uncertainty are among the major sources of stress in ATC (Bongo, 2017; Lecchini-Visintini, & Lygeros, 2010). Increased workload, continuous monitoring, and communication complexities were also identified as stressors. These findings emphasize the need for strategies to mitigate stress and improve psychological well-being among controllers during the UAV integration process. The non-ATS-providing group had higher levels of concern about regulatory challenges and communication complexities. This group may perceive UAV integration as more challenging and less familiar than the ATS-providing group.

The analysis of performance errors showed moderate concern for all error types, with communication errors and misidentification/loss of separation scoring the highest. This highlights the importance of developing clear communication protocols and procedures to minimize the risk of errors (Gupta, Jain, & Vaszkun, 2016; Kozak, Platenka, & Vrsecka, 2022). Additionally, concerns regarding procedural errors, inattention/overload errors, and decision-making errors emphasize the need for ongoing training and support for controllers as they adapt to managing a more complex airspace environment. Interestingly, technology-related errors received the lowest mean score, suggesting that controllers have greater confidence in technology compared to human factors. However, it is crucial to acknowledge that even with reliable technology, human interaction points can still introduce errors. Additionally, it was found that the non-ATS-providing group has a higher level of concern regarding communication errors and technology-related errors. The ATS-providing group's confidence in technology and their greater experience may be effective in reducing errors.

Finally, the study explored various mitigation strategies for addressing the challenges of UAV integration. The highest scores were attributed to enhanced communication protocols, collision avoidance systems, and geofencing/no-fly zones. These findings highlight the importance of technological advancements, clear communication protocols, and well-defined airspace restrictions for safe and efficient UAV integration. Additionally, controllers emphasized the need for updated regulations, comprehensive training programs, and proactive risk assessment and management strategies. Furthermore, no significant differences were found between ATS-providing and non-ATS-providing groups. Both groups placed similar importance on strategies such as communication protocols, collision avoidance systems, and regulatory framework updates.

6. Conclusion

This study examined the integration process of UAVs into airspace from the perspective of air traffic controllers. The findings of this study about integrating UAVs into controlled airspace are critical for the future of aviation.

The potential for mid-air collisions due to limitations in UAV technology and regulatory gaps emerged as a prominent concern, alongside challenges in managing UAV-related risks and communication difficulties. However, it is noteworthy that while training received the lowest mean score among the identified concerns, controllers may perceive it as a manageable challenge through additional training efforts. The urgency for advancements in UAV technology, the development of a comprehensive regulatory framework, and robust risk management strategies are highlighted as essential steps towards addressing these challenges effectively. Notably, differences between ATS-providing and non-ATS-providing groups regarding the perceived difficulty of the regulatory framework suggest varying levels of familiarity and confidence in existing systems. Moreover, workload factors associated with UAV integration, such as diverse operating characteristics, complexity of integration, and emergency response procedures, underscore the need for adaptations in existing ATC procedures and training programs. While concerns about adapting to new technologies exist, particularly impacting the human-machine interface, the belief in successfully adapting existing ATC systems prevails among the ATS-providing group. The study also highlights UAV integration as a significant source of stress for air traffic controllers, with complexity, uncertainty, and safety concerns ranking highest. Mitigating stress and improving psychological well-being among controllers are considered crucial, given the identified stressors and their potential impact on operational efficiency. In terms of performance errors, communication errors and misidentification/loss of separation rank highest, underscoring the importance of clear communication protocols and ongoing training for error mitigation. Despite controllers' confidence in technology, acknowledging the potential for human-related errors remains crucial. Finally, exploring mitigation strategies, such as enhanced communication protocols, collision avoidance systems, and geofencing/no-fly zones, underscores the importance of technological advancements and regulatory compliance. Both groups, ATS-providing and non-ATS-providing, converge on the significance of these strategies, emphasizing the need for unified approaches in addressing the challenges of UAV integration.

The focus on the perceptions of air traffic controllers in a specific region and the ongoing development of UAV technology and regulations are considered limitations of the study. In light of these limitations, continuous research and collaboration among all stakeholders are crucial. These stakeholders include different air traffic control authorities, UAV manufacturers, regulatory bodies, and legal experts. Their collaboration is essential to develop flexible mitigation strategies that can adapt to advancements in UAV technology and operational demands while complying with evolving legal frameworks and regulations.

Specifically, air traffic control authorities must work closely with UAV manufacturers to ensure that the technology meets safety and operational standards. Regulatory bodies need to keep up with technological advancements to update regulations accordingly, ensuring that new UAV systems are integrated safely into existing airspace structures. Legal experts play a critical role in interpreting and shaping laws that govern UAV operations, ensuring that these laws protect public safety and privacy without stifling innovation.

Moreover, this collaborative effort is key to ensuring a safe and successful integration of UAVs into the aviation sector. By maintaining regulatory compliance and addressing potential operational challenges, stakeholders can mitigate risks associated with UAV integration. It is also important to consider the impact of UAV operations on traditional manned aviation, ensuring that both can coexist safely and efficiently within the same airspace.

Therefore, it is recommended that future studies focus on the comprehensive impact of UAVs on air traffic operations and the development of regulations within this collaborative framework. Such studies should investigate how different regions manage UAV integration, the effectiveness of various mitigation strategies, and the long-term implications of UAV technology on air traffic control. By doing so, researchers can provide valuable insights that will help shape policies and practices, facilitating the smooth integration of UAVs into the global aviation system. This approach will not only enhance safety and efficiency but also promote innovation and growth within the UAV industry.

Ethical approval

Yes, this study received ethical approval from the Bartin University Social and Human Sciences Ethics Committee by Protocol Number 2024-SBB-0034 (2024/03/14).

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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