https://doi.org/10.1590/jatm.v17.1396 REVIEW ARTICLE

A Systematic Literature Review on Spoofing and Jamming Approaches in Unmanned Aerial Vehicles Navigation

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ABSTRACT

In the past decade, there has been a significant increase in the development and utilization of unmanned aerial vehicles (UAVs) across various industries. Factors such as remote control, payload capacity, versatility, precision, and confidentiality have fuelled interest in UAVs for multiple applications. However, UAVs' navigation and communication systems are increasingly vulnerable to various security threats, with the most concerning being the risks associated with Global Navigation Satellite System (GNSS) technology, such as spoofing and jamming. This paper presents a comprehensive analysis of UAV navigation security, drawing on recent peer-reviewed journals to identify and address gaps in current research. Machine learning and blockchain show promise but face scalability challenges. This review identifies underexplored gaps in environmental resilience. It examines the root causes of GNSS-related challenges, potential solutions, and promising research directions in the field of UAV navigation security.

Keywords: UAV; GPS; Security; Spoofing; Jamming.

INTRODUCTION

Unmanned aerial vehicles (UAVs) were initially used in military applications to engage in air-to-ground combat, surveillance, and target tracking in hostile environments. Nowadays, UAVs are also employed in various civilian applications such as agriculture (Acuna *et al.* 2018), cargo transport (Yang *et al.* 2016), and military support (Rahardi *et al.* 2020), as well as exploring inaccessible zones and delivering data to and from areas with no network infrastructure (Sedjelmaci *et al.* 2018). With the rapid development of aerial vehicle technology, satellite navigation systems have become indispensable. UAVs, or drones, and overall unmanned aerial systems (UAS) utilize Global Navigation Satellite System (GNSS) signals for navigation. GNSS can provide all-weather services that include positioning, navigation, and timing globally, which have been widely adopted in daily life for various applications. The Global Positioning System (GPS), GLONASS, BeiDou Navigation Satellite System (BDS), and Galileo are the most well-known global navigation systems.

This paper aims to analyze existing studies, collect findings, and summarize empirical evidence regarding GNSS security for UAVs, to secure their maneuvering in general and task accomplishment in particular. The comprehensive and in-depth analysis focuses on UAV applications, challenges related to both commercial and military UAVs, and future-generation work as outlined in Fig. 1. The research focus was addressed by formulating three research questions, as shown in Table 1.

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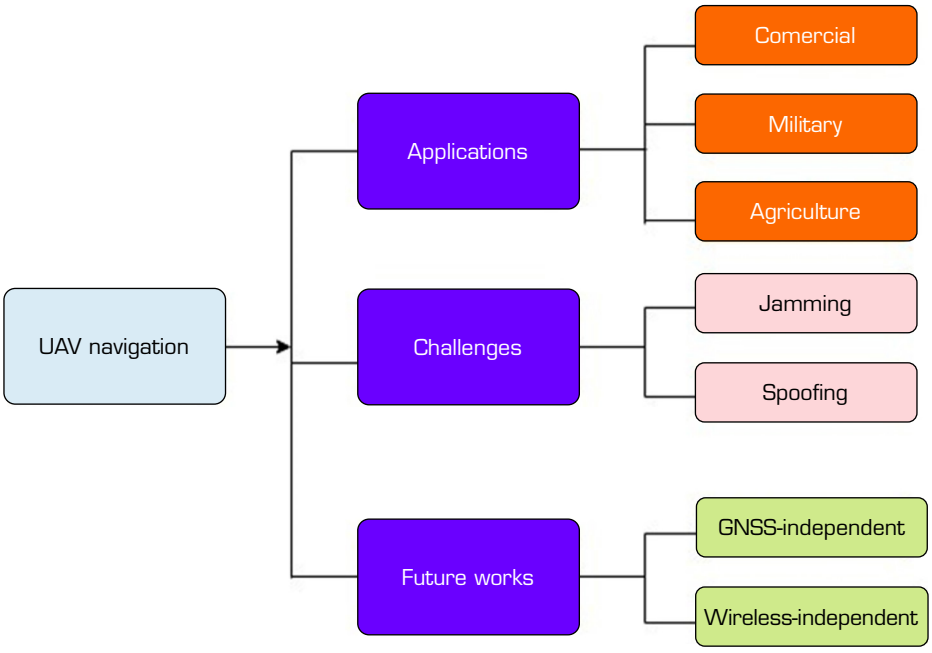


Source: Elaborated by the authors.

Figure 1. General framework of the research.

Table 1. Questions and their significance.

Research questions	Significance
How do UAS that use GNSS protect themselves against different security threats?	Describe how serious those threats are to the navigation of UAVs.
How are security threats addressed?	Evaluate the effectiveness and strength of the method.
What are the limitations of existing works?	Shows what needs to be done to enhance UAV network security.

Source: Elaborated by the authors.

The research questions, their significance (drawn from various research papers and in-depth critical analysis), and the approach are discussed.

A study on GNSS navigation was conducted using a pool of 90 primary works identified and collected up to 2024 to support UAV security. Research in this field can begin by using this pool as a foundation for developing a related research project.

The pool of primary studies was further filtered based on quality assessment criteria, resulting in a selection of 60 primary studies. These can serve as a reliable basis for further benchmarking and security evaluation.

A meta-analysis was presented on the measures implemented to improve the security of UAV maneuvering against jamming and spoofing threats.

Several issues and challenges exist in implementing security measures for UAV navigation.

The UAV's physical elements employ a flight controller with a network of sensors to communicate with the ground control system (GCS) (communication link). Accordingly, a UAV system is vulnerable to attacks that target the cyber and physical elements, the wireless link, or a combination of multiple components. Besides, the environment can block the wireless link between UAS; sensors are vulnerable to attacks differently, such as blocking, jamming, and spoofing (Altaweel *et al.* 2023; Wan *et al.* 2020). The following consequences of jamming are anticipated: drone loss, mission termination, or range restriction. If a UAV is unprotected and enters a jammed area, its mission will likely fail.

The aviation industry relies on GNSS for navigation and localization systems. The majority of recent studies use GNSS to locate drones accurately. However, there are some situations where GNSS precision may not be appropriate, leading to security threats in

the industry (Motlagh *et al.* 2019). Many studies on GNSS spoofing attacks have been reviewed, revealing various approaches being taken. Some studies are focused on responding to these attacks. In contrast, others propose using localization methods to detect, escape, and reduce technological threats, specifically focusing on spoofing issues in UAS, as discussed in Arteaga *et al.* (2019).

This paper introduces a novel approach to understanding the security risks associated with UAV spoofing and jamming attacks against drones. Specifically, it examines how vulnerable these drones are to companies that rely on GNSS. Additionally, a summary of research on jamming and spoofing vulnerabilities is presented. The review includes an assessment of the scalability, performance, and inherent barriers found in primary studies related to GNSS spoofing attacks and their interoperability in achieving goals. Through critical analyses, the topics that have been addressed are evaluated, gaps are identified, and suggestions for further research are proposed. Additionally, the research explores opportunities for collaboration among various research communities, the UAV industry, and related fields to address GNSS-related challenges. Existing techniques for mitigating jamming and spoofing are examined, providing a methodology that can assist practitioners in developing novel approaches to address problems beyond current solutions. The contribution of this paper can be presented as follows:

- Create awareness about jamming and spoofing on UAVs.
- Show the vulnerabilities of GNSS-dependent drone industries.
- Show how researchers are addressing spoofing and jamming issues.
- Examine the performance, scalability, and natural obstacles to the interoperability of UAVs.

The remainder of the paper is organized as follows: the introduction is presented first, followed by related works and UAV security threats. Security enhancement approaches are then discussed. A discussion section precedes the conclusion and future work, and references are provided at the end.

Related work

In this systematic literature review (SLR) study, the focus is primarily on targeted UAV cyber threats and related vulnerabilities. Different flaws in communication, sensors, and system configuration errors are identified (Rugo and Finanza, 2022). Ferrão *et al.* (2024), Gupta *et al.* (2023), Mukkath *et al.* (2023), and Radoš *et al.* (2024) highlighted sensor spoofing/jamming and malware as the most cited threats. To show research related to UAV spoofing and jamming problems, this study analyzes previous work based on the addressed problem research intention, applied methods, and the issues not covered.

Spoofing

Detection of UAV security threats

The standard Kalman filter (KF) is commonly employed for state estimation and spoofing detection in the presence of Gaussian additive noise to detect process (Yoon *et al.* 2019). Most drones utilize GPS and an inertial measurement unit (IMU) to mitigate issues stemming from GNSS problems. In normal operation, the state estimator operates in a default mode using GPS and the IMU to estimate the drone's status and detect potential attacks. If an attack occurs, the system transitions to an emergency mode, relying exclusively on the IMU for situational assessment. Once the attack detector confirms that GPS signals are no longer compromised, the ground system can revert to default mode for state estimation. However, these computational time and processes, along with the switch back to a robust mode, are time-consuming, which reduces the system's overall performance and efficiency.

Blockchain technology offers a novel approach to combating spoofing. Given that UAVs and other wearable communication devices use GPS positioning to transmit location-based signals, an attacker might attempt to alter a targeted UAV's GPS address, thereby affecting its actual position. Blockchain addresses this by securely storing UAV location data, allowing authorized users to access the data within a selected block. Despite its benefits, this method relies heavily on GPS signals and assumes that devices maintain a single, consistent position, which is not always the case in real-world scenarios (Satheesh Kumar *et al.* 2021).

Mitigating techniques

Zhu *et al.* (2019) suggested that personal devices could serve as additional sensors to help autonomous systems detect UAV hacking attacks using comparative human geo-location relative to the typical UAV-equipped gadgets. However, this process does not consider natural factors that could impair human and camera vision.

To determine the presence of an assault, Manesh *et al.* (2019) presented a supervised machine-learning method based on artificial neural networks (ANN). In this method, incoming GPS signals, whether real or fake, are input into the algorithm. Factors such as satellite number, carrier phase, pseudo-range, Doppler shift, and signal-to-noise ratio (SNR) were thoroughly analyzed to enhance accuracy and detection likelihood and reduce false alarms. While this approach attacks, it does not address performance issues or GNSS signal unavailability.

To explore space environment data, Basan *et al.* (2022) utilized the Kullback–Leibler divergence (KLD) value for individual time intervals and stored a summary of the findings in a time series. Subsequently, entropy calculations were conducted for the collected cyber-physical parameter values, revealing that a higher entropy value indicates an attacker's presence. The study relies on GNSS signals, which can be unavailable due to natural or malicious interference.

Research on GNSS spoofing attack detection strategies has been approached from various angles, with researchers noting limitations in existing methods. To address these challenges, two dynamic-based selection techniques were proposed to identify GPS spoofing assaults on UAVs (Talaei Khoei *et al.* 2022). Both techniques utilize supervised machine learning classifiers. They involve training and classification, feature selection, data pre-processing, and the construction of specific datasets. While these methods demonstrate better detection performance, they still depend on the GNSS system, which is beyond their control. Consequently, they do not resolve issues related to GNSS signal availability.

Machine learning for UAVs is an advanced approach to securing them from various spoofing attacks. UAVs are vulnerable to GPS spoofing attacks, where malicious actors transmit fake GPS signals to deceive the UAV's navigation system. This can lead to the drone deviating from its intended path, crashing, or even being hijacked. Machine learning offers powerful tools to detect and classify these spoofing attempts, enhancing UAV security and supporting the design mitigation strategies.

A central trust monitoring method is used to monitor the behavior of multiple UAVs in real-time while in flight and to identify any potential anomalies (Satheesh*et al.* 2021). In this method, the trust score of each UAV is determined and compared with the trust scores of neighboring UAVs. If a UAV's trust score falls outside the expected range due to environmental conditions affecting all nearby UAVs, it is considered under attack. This method is crucial for completing tasks once UAVs have been identified as spoofed, reporting, or being overlooked. Normal and abnormal case-based scenarios are also utilized to detect spoofing attacks (Ferrão *et al.* 2020). Security and safety metrics are also established with smartphone apps and the health, mobility, and security-based data communication architecture for unmanned aircraft systems (HAMSTER) architecture using Wi-Fi, smartphones, ground stations, and GPS. These measures are implemented unless they impact the system. Overall, these systems detect spoofing attacks within a specific area and environment, which helps address scalability and jamming issues. Voting techniques and a support vector machine-based (SVM) machine learning model are used to protect UAVs from GPS spoofing attacks.

Shafique *et al.* (2021) proposed a method for distinguishing between real and fake signals using several machine-learning methods. They employed deep learning techniques for gathering massive amounts of data and machine learning-based intrusion detection systems (IDS) to identify rapidly occurring attacks. Various machine-learning models are created using K-fold analysis to select the K-learning models used for voting. If the attacker remains present for an extended period, the proposed method will prevent the UAV from acting until it detects a valid GPS signal. However, performance issues beyond jamming are not considered.

Basan *et al.* (2021) offered a technique for spotting anomalies and spoofing attacks on UAVs using information collected and assessed from the drone's sensors. They have suggested using UAV sensors to create an autonomous system for spoofing attacks and detecting them. However, the system faces challenges such as dependency on the GNSS system, susceptibility to performance issues, and signal unavailability.

To counter the UAV control signal spoofing assault (Wang *et al.* 2020), a physical layer method has been suggested. Their goal was to locate the UAV-side source of the received signal. They used the channel's Rician factor, the distance-based path loss, and the angles of arrival. The signal is determined using the generalized log-likelihood radio test methodology. The suggested effort can locate the source and notify the GCS controllers; however, it does not address jamming or efficiency problems in its operation.

Detecting GPS-spoofing attacks on UAVs is an advanced and innovative method that involves predicting the flight path in advance at specific intervals using the long short-term memory (LSTM) algorithm. This is achieved by capturing

speed, direction, and distance from the starting point (Huang and Wang 2018). When the UAV's positioning signal deviates from the recorded route in the dataset, it is identified as a spoofing attack. However, the effects of this attack on performance, the time in case of repeated attempts, and the lack of consideration for jamming represent gaps that require more advanced methods.

A study by Shafique *et al.* (2021) employs a convolutional neural network (CNN), satellite images, and a camera for image recognition, classification, and segmentation. By comparing satellite imagery with real-time aerial photos, GPS spoofing attacks against UAVs can be detected. However, GNSS signal variations and lighting conditions may influence the intended outcomes.

Asif *et al.* (2023) proposed the IDS system, which utilizes generative adversarial network learning and adversarial learning methods to address the vulnerabilities of adversarial attacks against jamming and spoofing. While these integrated learning approaches show promise, natural obstacles, denial, and signal perturbations from the source have not yet been fully detected and solved.

Table 2 summarizes various methods for detecting and mitigating spoofing attacks, detailing their goals, approaches, and research gaps. It outlines that the reviewed studies do not address climate concerns, signal unavailability, or mission accomplishment capabilities.

Table 2. Summarizes recent research on GPS spoofing detection and mitigating techniques.

Related work	Security problem	Aims	Methods	Concepts not covered
Wan *et al.* (2020)	GNSS spoofing attack	Mitigating a spoofing attack	Cumulative sum (CUSUM), unscented KF (UKF), and KF	Efficiency issues
Jansen *et al.* (2018)			Air traffic monitoring	Efficiency issues
Yoon *et al.* (2019)			Gaussian and standard KF	Efficiency issues
Satheesh Kumar *et al.* (2021)			The Ethereum network measures a time series of signals	Jamming issues, mobility issues
Zhu *et al.* (2019)		Spoofing attack detection through signal behavior analysis	Humans as sensors	Climate
Basan *et al.* (2022)			Analyze the space environment	Unavailability, performance
Keshavarz *et al.* (2020)			UAV behavior analysis method	Performance issues
Huang and Wang (2018)			Physical layer signal behavior	Performance issues, jamming issues
Basan *et al.* (2021)			Sensors	Performance, jamming
Ferrão *et al.* (2020)			Case study with HAMSTER and smartphone apps	Scalability, jamming
Manesh *et al.* (2019)		Spoofing attack detection through machine learning approaches	Supervised machine learning with ANN	Jamming issues
Talaei Khoei *et al.* (2022)			Multiple machine learning classifiers	Performance, unavailability
Shafique *et al.* (2021)			Machine learning	Performance, jamming
Wang *et al.* (2020)			Machine learning LSTM algorithm	Performance, jamming
Xue *et al.* (2020)			Deep learning	Performance, unavailability
Asif *et al.* (2023)			Generative adversarial network and adversarial learning	Scalability, natural obstacles

Source: Elaborated by the authors.

Jamming

Detection

Sedjelmaci *et al.* (2018) proposed an IDS to protect networks from internal and external threats. Upon detecting spoofing, the system logs and relays the attacker's location and signal strength intensity (SSI) to the ground station. If jamming is detected, it sends an intrusion report, including the suspected transmitter's identity (e.g., a UAV) and the jamming type (deceptive or random), to the ground station. This method necessitates continuous monitoring of both the environment and the UAVs. The ground station controllers determine whether to proceed with the mission. However, this approach does not account for natural obstacles to GNSS and its link system.

Because traditional jammer localization via trilateration applies only to a single jammer, and given the availability of commercial GPS jammers, the risk posed by multiple jammers increases. To address these challenges, Bhamidipati and Gao (2019) and Ni *et al.* (2024) proposed simultaneous localization of jammer and receiver (SLMR) algorithms using IMU, ultra-wideband (UWB), camera, LiDAR, a cellular connection, and Wi-Fi through networked UAVs. This can be implemented using resilient stationary UAVs and network resources. However, UAV payloads cannot control natural environmental factors like jamming. Additionally, the method is resource-intensive, and jamming can result from either intentional intrusion or unintentional natural obstacles. Scholars mainly focus on mitigating deliberate jamming, which remains challenging as adversaries enhance their jamming capabilities. Natural interferences are also addressed, though usually temporarily, and researchers aim to ensure the safe return of UAVs rather than mission completion.

Mitigating techniques

Acuna *et al.* (2018) proposed a method for situations where external localization systems, such as GPS, are not available or reliable. In this approach, an unmanned ground vehicle (UGV) is used as a guide during UAV landing. However, the method is limited in scalability since it does not apply to flying missions.

Rezgui *et al.* (2019) and Wang *et al.* (2018) explored jamming mitigation techniques that leverage energy harvesting and game theory to address the effects of GNSS jamming. These approaches serve as countermeasures against intentional jamming attacks. The Nash equilibrium and frequency hopping strategies between the jammer and defender represent a viable method for mitigating jamming attacks involving a single adversary. However, a comprehensive solution remains elusive when faced with multiple jammers and natural interference.

Tedeschi *et al.* (2020) employed a technique used in multi-view learning and manifold alignment, particularly for analyzing datasets with multiple related but different representations. They called it the JAMming Methods (JAM-ME) algorithm, a jamming-based navigation technique that utilizes the jamming signal to estimate the jammer's location. This estimated location is then used as a radio beacon to determine the drone's relative position to the target. Alternatively, the adversary could modify the drone's firmware following the authors' algorithm, thus implementing a jamming-based navigation system. Once the adversary's position is determined, the system adjusts its position to achieve its objectives. While the jamming-based navigation method is an effective countermeasure that allows the UAV to complete its objectives despite existing ongoing jamming efforts, it becomes increasingly difficult as the number of jammers and sources of natural interference increases.

Li *et al.* (2019) implemented a strategy that utilizes multiple eavesdroppers with imprecise location data and a cooperative jammer UAV transmitting interference signals to confuse the eavesdroppers. This approach optimizes the flight paths and transmission power of both UAVs to maximize the system's worst-case secrecy rate. A block coordinate descent and successive convex optimization technique was proposed to iteratively optimize the UAV's power, the source UAV trajectory, and the jammer UAV trajectory. This method secures UAV communication using multiple devices to mislead the jammer UAV. However, natural interference remains a challenge in this secure communication approach, and it is resource-intensive.

Mah *et al.* (2019) developed a wireless relay network that uses a UAV relay to mitigate jamming. Their work optimizes the UAV's flight path to maximize the signal-to-interference-plus-noise ratio (SINR) at the receiver, enhancing the network's performance and robustness against jamming. A jamming-immune control channel employing strong error control coding facilitates the exchange of estimated jamming parameters from the UAV to the base station and flight path control information from the base station to the UAV. While some jamming parameter estimations occur onboard the UAV, most signal processing and optimization tasks are

handled by the base station. Although the approach effectively evades jammers, it does not protect against natural interference and is resource-intensive.

Scholars are currently exploring a variety of options to develop jamming solutions. The most commonly used approach in GNSS-denied indoor activities is computer vision maneuvering. In a study by the authors, Valenti *et al.* (2018) utilized an extended KF (EKF) to estimate poses. This estimation relies on data from IMU, gyroscope, and computer vision algorithms incorporating four virtual cameras and landmark localization. These devices and algorithms are used for obstacle detection and appropriate responses. While effective in familiar, stable environments, this approach is limited in outdoor conditions.

Tang *et al.* (2019) demonstrated a highly developed flocking's simultaneous localization and mapping system (SLAM) that effectively integrates several cutting-edge technologies, such as LiDAR-based SLAM and a visual system for nighttime and daytime sensing without constant wireless transmission or GPS signals. Although it reduces network overhead and can fly in any light condition, it is difficult to operate without wireless connectivity and a GNSS signal.

Even when the GNSS signal is unavailable for various reasons, the UAV does not rely solely on its onboard or external sensors for navigation. In addition to GNSS, several other types of navigation systems have been utilized. For example, Zhou *et al.* (2018) proposed vision-based localization using a low-cost IMU, creating a powerful vision-based inertial navigation system (VINS). This system also includes a minimal ultra-lightweight sensor suite enabling robust autonomous flight. However, this VINS is unsuitable for outdoor navigation due to challenges such as natural illumination variations and scalability problems.

In situations where GPS is available, approaching a target can often be achieved by simply sharing GPS data between the UAV and the target. For example, Nguyen *et al.* (2019) addressed the problem of autonomous UAV docking onto a moving UAV from a distance. They integrate UWB and vision sensors to provide accurate and reliable relative localization (RL). They integrated UGV, vision sensors, and UWB to provide accurate and reliable RL for landing. While applicable in a resilient environment, this method may not be suitable for unknown outdoor conditions.

An alternate localization technology for landing instances was proposed by Dobrev *et al.* (2018). This system utilizes a single ground-based radar station and a miniature radar unit on the aircraft, employing wireless local positioning to estimate the UAV's 3D position. This equipment is used for take-off and landing events when flights are hindered. However, the UAV cannot be localized if there is no GNSS signal during operation, nor can the system be used if the primary ground radar is damaged.

The current RL approach, based on persistent excitation, suffers from accuracy loss, error accumulation, and divergence (She *et al.* 2020). Sensor synchronization, UWB, and IMU sensors were utilized to address these challenges. This method requires a group of UAVs to fly together on a single mission, making it a viable solution when a GNSS signal is unavailable. However, a limitation of this approach is its inability to determine the UAV's goal or objective, which can lead to scalability issues.

GNSS signals are weak and easily jammed or interfered with in various ways. When a disruption in the GNSS signal occurs, White *et al.* (2021) presented an alternative navigation approach using a synthetic aperture radar (SAR) system and a GNSS signal. While promising, this method requires a radar system to function. Therefore, if either GNSS or a radar system is unavailable, the system cannot operate. Additionally, these factors are not taken into consideration. Li *et al.* (2020) introduced a single fixed-base station localization wireless positioning method and validated it with UAV flight data. This method resolves any issues related to GNSS navigation. However, networks and base stations are limited in their ability to cover large areas due to natural obstructions, making them non-scalable and susceptible to environmental barriers.

The autonomy of UAVs has made it difficult for them to navigate uncharted territory. Qin *et al.* (2019) suggested utilizing GNSS-denied maneuvering with the assistance of UAVs to address these issues. They integrated vision technology through a wireless link to navigate even without GNSS signals in a safe and well-lit environment. Therefore, flying autonomously becomes challenging under these circumstances. Habib *et al.* (2020) focused on enhancing UAV navigation technology to facilitate site inspections. They measure height, x-y position, and ground velocity using an optical flow sensor and sonar. Despite its improvements over current technologies, scalability issues and natural barriers persist.

Table 3 provides a summary of the ways to mitigate and detect jamming attacks and displays the objectives, strategies, and topics not covered in the research articles. The studies do not address climate issues, signal reliability, scalability, or mission accomplishment competencies.

Table 3. Summarizes recent research on GPS jamming detection and mitigating techniques.

Related work	Security problem	Intention	Approach	Method	Issues not covered
Sedjelmaci *et al.* (2018)	Jamming	Detection	Using the GNSS signal	IDS	Natural obstacles
Tedeschi *et al.* (2020)				JAM-ME algorithm, change location	Performance, environment
Li *et al.* (2019)				Employ many confusing devices.	Natural obstacles and costly
Rezgui *et al.* (2019)				Frequency hopping and energy harvesting	Natural obstacles and costly
Bhamidipati and Gao (2018)				SLMR algorithm, sensors, and resilient network	Performance, environment
Acuna *et al.* (2018)		Mitigation technique	GNSS denied using vision-based navigation	Vision data with UGV	Scalability
Valenti *et al.* (2018)				Vision data with EKF	Scalability
Tang *et al.* (2019)				LiDAR-based SLAM and a visual system	Scalability
Zhou *et al.* (2018)				Vision-aided inertial navigation system (VAINS)	Scalability
Nguyen *et al.* (2019)				Vision sensors UGV, UWB	Scalability
Dobrev *et al.* (2018)			GNSS denied using alternative localization	Radar-based wireless localization	Scalability
She *et al.* (2020)				UWB and IMU sensor synchronization	Scalability
White *et al.* (2021)				GNSS and SAR	Scalability
Li *et al.* (2020)				Wireless links and base stations	Scalability, natural obstacles
Qin *et al.* (2019)				Wireless links and UGV alt	Scalability, natural obstacles
Habib *et al.* (2020)				Wireless links, local positioning, and EKF	Scalability, natural obstacles
Mah *et al.* (2019)				Wireless relay network	Performance and natural obstacles
Arslan *et al.* (2016)	Spoofing	detection	Using machine learning	Modelling approaches	Performance and natural obstacles

Source: Elaborated by the authors.

Threats of syncretization and methodology

With the expansion of UAV usage and available facilities, the UAV wireless network is vulnerable to several hostile threats, such as eavesdropping, jamming, and spoofing attacks (Liu *et al.* 2021; Majeed *et al.* 2021). Modern aviation technologies cannot be effective without securing the navigation system, as it aids navigation to destinations quickly and safely. Without successful mission accomplishment, various security threats such as jamming, spoofing, and eavesdropping can impact the navigation system. Devices relying on GNSS can be interfered with and interrupted by fake GNSS signals, causing flying objects to veer off course and miss their destinations. GNSS spoofing represents a significant threat to national industry security. Multiple jammers on a single device pose an immediate threat (Alrefaei *et al.* 2022; Bhamidipati and Gao 2019; Junzhi *et al.* 2019; Wang *et al.* 2019; 2020; Xu *et al.* 2021; Zhi *et al.* 2020).

Review criteria

In line with established protocols for systematic literature reviews (SLRs), this study defines research questions, designs search strategies, and applies inclusion and exclusion criteria to guide the research process. Therefore, a wide variety of sources is available on the topic, contributing to the fact that this result is based on a broad range of sources.

Literature search method

The SLR was conducted following normative recommendations to answer specific research questions by collecting literature to provide a longitudinal and representative view of works (Kitchenham and Charters 2007). To obtain an unbiased and complete picture, many sources were explored, including major online databases: Institute of Electrical and Electronics Engineers Xplore Digital Library (IEEE Xplore), Association for Computing Machinery Digital Library (ACM), Multidisciplinary Digital Publishing Institute (MDP), Wiley Online Library, ResearchGate, and Science Direct/Elsevier.

The major databases were explored due to their extensive collections of journal articles and conference proceedings, which enabled the examination of various studies on security issues and solutions for GNSS-based UAV navigation systems.

Selection of primary studies

Primary studies were collected using keywords in the search facility of selected databases. Generic search terms were used to ensure broad results by placing the primary search terms between logical AND/OR operators. For example, searches were conducted using "UAV" AND "GPS", AND "Security" to include all relevant data, and also for AND "GPS navigation security" OR "GPS Security" AND "GPS jamming" AND "GPS spoofing" AND "UAV navigation security" AND "UAV security" to achieve the optimal filtering results. The searches were conducted in 2024, considering papers published from 2016 up to that date. Search results were subjected to a filtering process after applying inclusion and exclusion criteria, resulting in a set of primary studies. These studies were then fed into a snowballing process to obtain further research studies in the targeted domain (Wohlin 2014). Forward and backward snowballing were applied iteratively until no further papers meeting the inclusion criteria were detected.

Inclusion and exclusion criteria

To ensure the identified relevant works aligned with the SLR, specific inclusion and exclusion criteria were defined. For a work to be considered in this systematic review, it had to report substantial empirical findings and be available in one of the online databases mentioned in the related work synthesization. Studies also had to be peer-reviewed, written in English, and focus on security threats, challenges, and solutions for UAV GNSS navigation systems. As shown in Table 4, key criteria were used to determine the inclusion or exclusion of the studies.

Table 4. Key inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
Must fall in the broader field of security UAV navigation, such as GPS spoofing and jamming, and GPS-denied navigation	If it falls outside the broader field of UAV navigation
Must present empirical data related to GPS spoofing and jamming attacks and GPS-denied navigation to provide security in the aviation industry.	Paper not published in the English language
Must have gone through a peer-review procedure, usually presented in a conference or journal paper form.	Grey literature
Presents GPS and link attacks, detection, and prevention	White papers

Source: Elaborated by the authors.

Distribution of papers

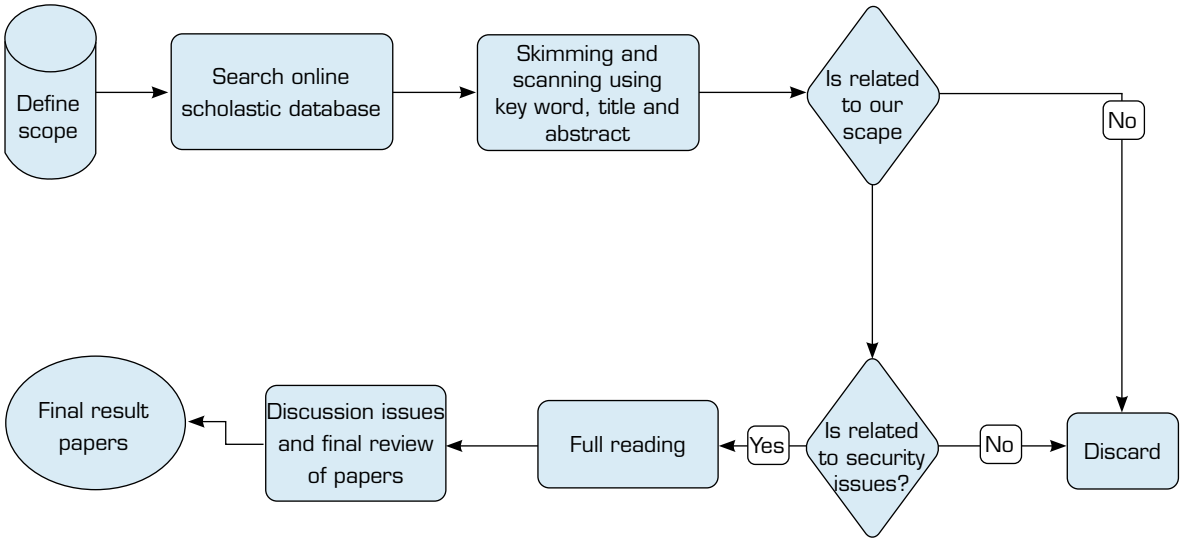
This paper aims to find suitable, reliable, and sufficient literature by exploring various online digital libraries based on the search keys described in the related work discussion. The digital libraries outlined in Table 5 were examined, given their widespread popularity and wealth of resources in the field, and the methodological framework is shown in Fig. 2.

After conducting a thorough review of relevant literature across various online databases, the material was scanned and skimmed to gather both a comprehensive overview and detailed information. The identified works focusing on security issues were then extracted and analyzed accordingly. These scholarly works are now prepared for in-depth examination as part of the SLR process.

Table 5. The number of papers from different online academic databases.

No.	Databases	# of papers	Related papers	Summarized papers
1	IEEE	210	57	55
2	MDPI	93	12	7
3	ACM	30	8	4
4	Elsevier	25	7	4
5	Wiley Online Library	15	6	3
6	ResearchGate	15	6	6
	Total	388	91	79

Source: Elaborated by the authors.



Source: Elaborated by the authors.

Figure 2. Methodological framework for the systematic literature survey.

Security threats

Jamming and spoofing can significantly impact the three pillars of cybersecurity: confidentiality, integrity, and availability. Table 6 visually represents the severity of these issues by presenting studies on spoofing and jamming from the past 11 years.

Table 6 represents the frequencies of spoofing and jamming studies in different years. However, the representation is based on the authors' findings and perspective and does not suggest that these are the only studies published in those years.

Table 6. How much jamming and spoofing are studied?

	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Jamming/spoofing	5	5	7	7	14	16	17	17	9	4	6

Source: Elaborated by the authors.

Spoofing is a technique that commonly includes jamming and more powerful signal attacks. In beaconing, beacons repeat and acquire signals after estimating the correct signal, resulting in the receiver receiving outdated signal data with inaccurate temporal information. Another type of spoofing involves overpowering authentic GNSS signals during the acquisition stage, leading to a loss of control over the UAV by the sources (Demir *et al.* 2020). This type of attack is more complex than jamming, as it involves passing off unauthorized signals as legitimate ones (Alrefaei *et al.* 2022; Cuntz *et al.* 2012).

A fake satellite signal is initially used in spoofing to deceive a GNSS receiver. This can be achieved with minimal power, a smart mode, and a small amount of false but highly misleading content to reach the desired interference goal. To target a specific victim, the spoofer alters the GNSS signal with subtle yet significant errors in position, velocity, and time (PVT), amplifies it, and rebroadcasts it (Ouyang *et al.* 2016).

Jamming is a harmful attack that disrupts communication between UAVs and other legitimate parties on the UAV network. It is essentially a denial-of-service (DoS) attack on a wireless platform, jeopardizing the system's availability by disrupting communication. Hackers target the channel node with radio waves using the jamming attack technique. There are four subcategories of jamming attacks: continuous, reactive, random, and constant. Despite numerous attempts to mitigate UAV navigation spoofing and jamming, these tactics are likely to persist until new vulnerabilities are exploited. Research summarized in Tables 2 and 3 suggests approaches that rely on GNSS and alternative navigation methods with various security measures to counter resilient jamming and spoofing techniques.

Methodology of security enhancement approaches for UAV navigation systems

Intrusion detection and prevention-based (IDP) solutions

The open, nature-affected, and insecure environments of wireless communication and navigation for UAS increase the industry's vulnerability to various communication, navigation, and weather-related issues. Scholars are working on securing communication in UAS through different approaches, including *IDP* methods. In a paper, a comprehensive review was conducted outlining approaches and research methods for detecting and preventing attacks in the UAS network to identify malicious abnormalities that harm the network. Researchers have implemented attack monitoring and response systems at the UAV and ground control station (GCS) levels by utilizing an IDS agent on each UAV. By identifying malicious abnormalities that could harm the network, researchers can categorize nodes as normal, aberrant, or suspect, focusing on preventing the spread of misleading information, GPS spoofing, jamming, and attacks involving black holes and grey holes.

Intrusion detection systems often use a collection of attack patterns to create the rules or a rules-based intrusion detection method for detecting abnormalities. A distributed intrusion monitoring and detection solution that is delay-tolerant is employed. This method allows each node to activate an IDS agent, listen to all packets within its radio range, and observe the UAV behavior as they move around the area (Sedjelmaci *et al.* 2018). Another strategy for ensuring UAV information security involves using mathematical techniques for outlier detection. Specifically, the KLD, in conjunction with the probability mass Function (PMF), can compare and quantify two probability distributions at various time points. This allows for characterizing normal behavior and then comparing the observed data's PMF to normal behavior, utilizing the KLD to identify anomalies by comparing the observed data's PMF to the established normal behavior, assuming the initial data samples are free of abnormalities (Basan *et al.* 2021).

According to Basan *et al.* (2022) UAV electromagnetic jamming security situation awareness is proposed using semantic analysis. The data source of semantic analysis is collected based on the subtle changes in the UAV state parameters during the electromagnetic interference process. Abnormal behavior detection is realized by a tracing comparison method. Subsequently, fuzzy logic reasoning is adopted to realize the semantic analysis of the link jamming and intrusion situation. Finally, the semantic evaluation of the link situation has been developed (Gao *et al.* 2020).

Drones need an IDS that uses deep learning to identify intruders and ensure a safe return. The proposed IDS combines self-taught learning (STL) with a multiclass SVM. This achieves a high detection rate even against unknown threats. STL, a deep learning algorithm for supervised feature learning, enables UAVs to navigate home in various situations. If a GPS signal is lost, the system initiates self-analysis and detection methods. Should the communication link between the UAV and its control station be compromised, the UAVs will attempt to reconnect or locate nearby UAVs to facilitate a safe return (Arthur 2019). In all these scenarios, however, security remains a concern, as hackers can exploit vulnerabilities in both the communication link and GPS.

Alternative localization

Localization is a critical concern for UAVs, especially in diverse applications like security. As Li *et al.* (2024) highlighted, accurate localization is essential for UAV safety and communication with ground sensors. This fundamental technique underpins the security and reliability of UAV operations. GNSS lacks the reliability to provide accurate and secure positioning. Cellular signal ranging and localization methods that can supplement or replace the system to aid UAVs in navigating to their destinations.

However, while the current mobile communication infrastructure and network can support sustainable ranging, localization, and logging of UAVs even in the absence of GNSS signals or signal manipulation, achieving sustained ranging and localization for UAVs remains a persistent challenge (Radoglou-Grammatikis *et al.* 2020).

Researchers have proposed an alternative localization method immune to GPS spoofing and jamming attacks, as GNSS localization and navigation are susceptible to various attacks. These alternative localization techniques are used in place of the well-known GPS signal. In a GPS-denied situation, a collaborative comparative positioning approach without infrastructure has been proposed using UWB technology (Guo *et al.* 2020). The increased use of GPS and reliance on UAS has raised concerns about the danger of jamming, making it a significant safety concern. As a result, a 24 GHz frequency radar system has been suggested as another localization approach (Dobrev *et al.* 2018).

UAVs equipped with vision navigation systems face challenges with lighting. Therefore, a weighted k-nearest neighbor algorithm positioning system has been developed (Hong *et al.* 2020). The authors have proposed improved persistent excitation based on RL to address UWB and RL. Each UAV is equipped with a UWB module and an IMU as onboard sensors to measure proportional distance and velocity (She *et al.* 2020). To improve positioning accuracy, four or more fixed base stations and mobile nodes are utilized using ranging information (Li *et al.* 2020).

Alternative localization is a popular method of GPS navigation that utilizes techniques other than GPS to protect users from threats associated with GNSS. However, these methods are vulnerable to environmental factors and a variety of threats.

Machine learning and deep learning

Recently, machine learning and deep learning technologies have been utilized for various applications, such as UAV networks for autonomous navigation and intrusion detection (Yin *et al.* 2024). A methodology has been proposed that incorporates a machine learning algorithm like the SVM to protect UAVs from GPS spoofing attacks. In their studies, the machine learning method and K-fold studies were performed to create additional learning models by selecting various K-fold values (Shafique *et al.* 2021). Artificial intelligence and neural network-based solutions have been developed to handle spoofing and jamming problems (Challita *et al.* 2019). Furthermore, methods like metrics-optimized dynamic selection and weighted metrics-optimized dynamic selectors have been suggested to identify the most efficient classifier for detecting attacks on UAV networks.

According to the authors, multiple machine learning classifier systems are preferable for identifying GPS spoofing attempts rather than using a single classical machine learning model (Talaei Khoei *et al.* 2022). The authors have introduced deep learning satellite image matching (Deep SIM), an approach to detecting GPS spoofing attacks against UAVs by comparing historical satellite images with real-time aerial images based on deep learning (Xue *et al.* 2020). Machine learning has also been proposed to detect and classify jamming attacks on UAVs. Signal-to-noise ratio (SNR), power threshold, and multiple orthogonal frequency division multiplexing (OFDM) parameters or features are passed to machine learning algorithms to detect and enable automatic jamming discovery (Pawlak *et al.* 2021).

These approaches are implemented to detect spoofing and jamming during UAV navigation. While they perform better than existing security approaches in reducing spoofing and jamming problems, they require all methods of navigation and linking for operation.

Vision-based navigation

To understand information from a distance, a visual device employing computer vision processing technologies is applied. Vision-based navigation has become increasingly important in various space applications, including hazard avoidance, landmark tracking during landing, and localization and mapping to increase autonomy and reliability (Xie *et al.* 2018). Vision-based navigation has emerged as an alternative to GPS in UAV networks due to GPS's vulnerability to ongoing spoofing and jamming attacks. An omnidirectional stereovision system creates a 3D model of the surroundings. A downward-looking stereo pair is used to calculate the drone's height above the ground and refine the pose estimate in a simultaneous localization and mapping method (Valenti *et al.* 2018).

An agile approach maneuver is proposed in which the target vehicle may move out of the vision sensor's range of view. The UAV tracks the UGV's motion, predicts it, and creates a smooth trajectory for approaching the projected point (Acuna *et al.* 2018). Researchers have used vision-based techniques to autonomously navigate UAVs, capturing real images during flight to predict and decide on a collision-free trajectory (Kanwal *et al.* 2021; Nguyen *et al.* 2019; Tang *et al.* 2019; Vanegas *et al.* 2018; Xie *et al.* 2018). These vision-based approaches are increasingly popular as an alternative to GPS-denied navigation for UAVs. However, they are effective only in a conducive environment and cannot fly or plan trajectories in the low-night, foggy, or low optical flow conditions (Cao *et al.* 2022).

Blockchain-based security approaches

Blockchain technology, offering properties like traceability, transparency, and auditability as an immutable distributed ledger, has enhanced security applications and is used in various fields to address challenges. In the context of the UAV network, blockchain is described as reducing security and safety hazards and increasing device reliability in a blockchain network compared to the central system GCS (Khan *et al.* 2021).

To reduce cyberattacks during communication and storage, blockchain technology features built-in cryptographic hash and smart contract capabilities to prevent such attacks. To address authentication and data-sharing issues, a blockchain-enabled, efficient, and secure data-sharing model for 5G flying drones has been proposed (Feng *et al.* 2020; 2021; Xenya and Quist-Aphetsi 2019). A scalable, advanced Byzantine fault tolerance protocol with the concept of blockchain of drone (BCoD) has been proposed to address low throughput, high latency, and lack of identity management issues in permissionless blockchain, proof-of-work (PoW), and proof-of-stake (PoS) consensus protocols. Additionally, it aims to provide an additional authentication and authorization layer (Singh and Venkatesan 2021) (Wang *et al.* 2024).

The Ethereum blockchain network has been utilized to prevent spoofing attempts. Aviation components added to the blockchain ledger are important for secure data transfer. If an attacker gains access to data in a single block within the network, the data remains unaffected due to the data integrity in the cryptographically secured ledgers. The blockchain network periodically verifies geolocation data, allowing for the rapid identification and discarding of inaccurate information. The verified data is then accessible for monitoring spacecraft and its operations through a distributed network (Satheesh Kumar *et al.* 2021). Elliptic curve cryptography and secure hash algorithm (SHA) are employed to encrypt technical data about devices and vehicle data, which is then stored on a public blockchain powered by Ethereum to facilitate seamless blockchain technology transactions. These methods ensure data security against ciphertext, plaintext, and stalker attacks (Ch *et al.* 2020).

Blockchain technologies, as discussed above, use a consensus algorithm to secure communication and data storage (Cheng *et al.* 2024). The consensus method identifies outlier and inlier threats, improving the accuracy of GNSS by enabling more precise comparisons. They function effectively in a network to prevent spoofing and unauthorized access. They are suitable for designing trusted networks within the current Internet of Drones (or UAVs, in general) and other devices. However, blockchain technology is susceptible to interference from the environment and jamming.

DISCUSSION

Scholars have utilized various approaches to enhance the security of UAV navigation systems. These approaches include security threat detection, threat prevention, and GNSS-independent navigation. The goal is to address the security issues faced by UAV navigation systems. Various methods have been employed within these approaches, which include IDS, IDP, machine/deep learning, log files, filtering algorithms, frequency hopping, IMU, inertial navigation system (INS), vision-based navigation, blockchain, and alternative localization. Despite these approaches and methods, they have not been evaluated for efficiency, cost, nature, and man-in-the-middle attack (MIMA) parameters as shown in Table 7.

Table 7. Security enhancement techniques.

Threats	Solution	Methodology	Critiques
GPS spoofing, jamming, and link/sensor attacks	Detection	IDS, machine learning/deep learning, sensors, log files	Missions will affect and cost another flight
	Detection and prevention	Filter algorithms, frequency hopping, machine learning with intelligence, IDP off-GPS with IMU	The number of attempts and attack methods makes the task difficult and is influenced by nature.
	Prevention	Blockchain, smart contract	MIMA, attacks within the system, and nature affected
	GPS denied	Vision-based with SLAM and INS, alternative localization, UWB, augmented reality sensors, and deep learning.	The link could be compromised and influenced by nature

Source: Elaborated by the authors.

Various strategies are being utilized to ensure the safe navigation of UAVs, as discussed above. Due to these strategies, UAV navigation is becoming safer in conditions that reduce associated risks. While each method has its limitations, the technology requires periodic updates to security measures to stay ahead of any new threats posed by attackers who may surpass existing measures. Therefore, as long as attackers do not exert significant effort, the security measures implemented by various academics will remain effective.

As shown in Table 8, the current safeguards against spoofing and jamming attacks are highly effective in achieving their intended objectives. The methods and techniques used to address these problems have been proven successful when dealing with jamming and spoofing individually. Tables 2 and 3 above illustrate that researchers actively work to identify and counteract jamming and spoofing attacks. Some researchers focus on developing detection and mitigation strategies that work as long as a wireless link and GNSS localization or any other form of localization are available. However, jamming issues can prevent any localization over the wireless channel, especially if the service provider denies access to the source. In such cases, natural interferences, like spoofing, deliberate or accidental jamming, and denial of services, can impact the effectiveness of mitigation strategies. Scholars' research on threat detection, root cause analysis, countermeasures, and performance challenges are summarized in Table 9.

Table 8. Summarized performance measure of the literature.

Issues	Methodology	Status	Drawback
Spoofing	Threat detection and prevention	Very good	Low-performance and resource-intensive
Jamming	GNSS-denied	Very good	Natural interferences

Source: Elaborated by the authors.

Table 9. An identified gap in the existing works.

Parameters	Wan *et al.* (2020)	Ferrão *et al.* (2020)	Bhamidipati and Gao, (2019)	Jansen *et al.* (2018)	Zhu *et al.* (2019)	Manesh *et al.* (2019)	Basan *et al.* (2022)	Talaei Khoei *et al.* (2022)	Keshavarz *et al.* (2020)	Dobrev *et al.* (2018)	Shafique *et al.* (2021)	Satheesh Kumar *et al.* (2021)	Yoon *et al.* (2019)
Threats detection	√	√	√	√	√	√	√	√	√	√	√	√	√
Root cause	X	X	X	X	X	X	X	X	X	X	X	X	X
Countermeasure	√	√	√	√	X	X	X	X	X	√	X	√	√
Performance	X	X	X	X	X	X	X	X	X	X	X	X	X
Environment	X	X	X	X	X	X	X	X	X	X	X	X	X

Source: Elaborated by the authors.

The biggest problem facing navigation systems is their reliance on wireless connections, whether through GNSS or other localization methods. These wireless communication vulnerabilities are precisely where jamming and spoofing attacks cause trouble. Since these technologies can be easily disrupted or compromised at their source, researchers have yet to find a comprehensive solution. While much research focuses on detecting and preventing these attacks, the effectiveness of these countermeasures is often not thoroughly evaluated. This lack of performance assessment means it is not yet clear how well they work. Environmental factors also significantly impact the reliability of current communication and localization methods. Conditions, clouds, or intentional jamming encountered during flight operations can lead to various issues: operational failures, mission failures, intermittent flights, and increased consumption of time and resources. When these problems occur, the objectives of the operation are not met, and resources are wasted.

The GNSS is crucial in the aviation industry, as aircraft are enabled to navigate to their destinations. However, GNSS is vulnerable to natural, weather-related, and intentional attacks. Spoofing and jamming are the most common problems encountered in the GNSS system, which can impact the aircraft's flight, the system itself, and even lead to crashes and theft of flying objects. Researchers are actively developing mitigation techniques to address these spoofing and jamming challenges. The solutions proposed by scholars still rely on GNSS and wireless communication technology, which may reduce the likelihood of the problems but not eliminate them. Natural, weather-related, and intentional jamming and spoofing attacks persist in this technological landscape, as the GNSS

system remains the backbone of wireless communication technology. The challenges encountered by UAVs due to jamming and spoofing can compromise their performance and successful mission completion. If the rates of successful mission achievement are diminished, costs will escalate, and the technology may become inadequate. Consequently, a navigation system is crucial to developing a novel and safe system for UAVs resilient to natural, weather-related, and intentional jamming.

CONCLUSION

This study researched and delivered the critical security challenges facing UAV navigation systems, focusing on security challenges presented by jamming and spoofing attacks. A range of mitigation techniques was explored, from various detection and prevention strategies to alternative navigation methods, all aimed at countering these sophisticated threats and other sensor-based attacks. Machine learning and blockchain techniques are promising in reducing or overcoming deliberate spoofing and jamming. Additionally, improving UAV performance and efficiency faces challenges, including man-in-the-middle (MITM) spoofing attacks and cost scaling. Machine learning and blockchain technology can help by clustering similar threats, spoofing, and jamming, allowing prioritizing and mitigation of the most severe problems first. Despite numerous proposed countermeasures, their effectiveness in truly addressing the root causes of vulnerabilities remains limited. The inherent reliance of UAVs on GNSS and wireless communication technologies, susceptible to disruption or denial of service, clearly signals the need for a more robust and resilient approach to navigation system security. In this comprehensive systematic review, the following contributions are proposed.

- Focus on root cause analysis: future research should prioritize identifying and addressing the fundamental causes of navigation security vulnerabilities, such as the inherent limitations of GNSS and wireless communication technologies.
- Evaluate performance metrics: the efficacy of proposed countermeasures should be rigorously evaluated based on their impact on mission performance, including factors such as mission success rate, flight time, and operational range.
- Explore alternative navigation technologies: investigating alternative navigation technologies, such as INS, vision-based navigation, and advanced sensor fusion techniques, can provide redundancy and resilience against jamming and spoofing attacks.
- Develop advanced detection and mitigation techniques: continuous research and development efforts should focus on creating sophisticated detection algorithms and adaptive mitigation strategies to counter evolving threats and improve the robustness of navigation systems.
- Conduct real-world testing and validation: thorough testing and validation of proposed solutions in realistic operational environments are essential to assess their effectiveness and identify potential limitations.
- Foster international collaboration: collaboration among researchers, industry experts, and regulatory bodies is crucial for sharing knowledge and establishing standardized security protocols and guidelines.

By addressing these challenges and leveraging emerging technologies, the aviation industry can ensure safety and reliability in the increasingly complex and adversarial operational environments of UAVs. UAVs are used for various purposes and missions, making them increasingly popular. The nature of UAV communications and navigation makes them susceptible to jamming and spoofing attacks, which can degrade mission performance and potentially lead to catastrophic social, economic, and political consequences.

Extended research is necessary to gain insights into the main threats, associated attacks, and available countermeasures. The methodologies used to analyze trends in navigation systems will provide essential knowledge for next-generation UAVs. Additionally, UAV systems must be tested without GNSS or any communication links, and the mission performance rate must be measured.

- As seen, natural interferences and GNSS systems are the primary causes of navigation security issues in aviation. Current research often overlooks the potential for intentional denial of service by GNSS systems and wireless communication providers. Future research should prioritize addressing these intentional threats.
- Alongside the security measures outlined in various research studies, it is essential to assess the extent to which these measures mitigate the root causes of security issues within navigation systems.
- Even though research has been conducted on various navigation security problems, it is recommended that solutions focus on addressing the root causes of navigation security system problems.

CONFLICT OF INTEREST

Nothing to declare.

AUTHORS' CONTRIBUTION

Conceptualization: Meheretu SE, Nigussie E, Gebremeskel GB, and Hailesilassie SY; **Methodology:** Meheretu SE and Gebremeskel GB; **Validation:** Nigussie E and Gebremeskel GB; **Formal analysis:** Meheretu SE; **Investigation:** Meheretu SE and Gebremeskel GB; **Data Curation:** Meheretu SE and Hailesilassie SY; **Writing - Original Draft:** Meheretu SE; **Writing - Review & Editing:** Meheretu SE and Gebremeskel GB; **Visualization:** Meheretu SE, Nigussie E, Gebremeskel GB, and Hailesilassie SY; **Supervision:** Nigussie E and Gebremeskel GB; **Final approval:** Gebremeslek GB.

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The data used in this study are available from the corresponding author upon reasonable request.

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