International Journal of Multidisciplinary Approach Research and Science
E-ISSN 2987-226X P-ISSN 2988-0076
Volume 3 Issue 03, September 2025, Pp. 1129-1141
DOI: https://doi.org/10.59653/ijmars.v3i03.1965

Emerging Trends and Technological Challenges in Avionics Systems: A Comprehensive Review

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Received: 29-07-2025 Reviewed: 05-09-2025 Accepted: 13-10-2025

Abstract

Avionics is quickly shifting from independent subsystems to completely integrated systems intended to leverage technology to raise safety, effectiveness and sustainability in aviation. This paper provides a broad, but intensive, examination of the emerging trends and technological challenges that mark avionics a modern era. Using recent literature from Scopus, Web of Science, IEEE Xplore, ScienceDirect and other venues, it brings together themes around communications, navigation and surveillance technologies; integration of unmanned aircraft, artificial intelligence and machine learning; digital transformation; sustainability; human factors; reliability; and advanced manufacturing. Additionally, it highlights how these technologies interact with other themes with relevance to avionics including cognitive radio, digital twins, and predictive analytics amid pressing challenges surrounding spectrum, increasing complexity of systems, certification, and cybersecurity. Instead of separating these themes, the paper highlights how they work together and must be considered as a whole to advance technology, operations, and human factors. Together, the synthesized themes construct a methodical synthesis of beacons across domains for new generation researchers, engineers and regulators in advanced avionics.

Keywords: Artificial Intelligence; Avionics Systems; Digital Transformation; Emerging Technologies; Unmanned Aircraft Systems; Reliability and Safety

Introduction

Advances in avionics systems now lead to hybrids of greater intelligence and cyber-physically networked systems that improve the performance of an aircraft, ensure safety over them, and manage air space, while providing seamless human-machine automation and better decisions and situation awareness (Sabatini et al., 2020). Today's aircraft design increasingly uses computer-aided optimization involving multiple variables to balance design trade-offs, improve efficiency, and speed up prototyping. (Smith et al., 2018). These advancements, collectively, yield aeronautical systems that are more agile, reliable, and efficient that can satisfy the upcoming charges to global airspace.

This paper explores the primary areas of advancement and technological challenges associated with the avionics industry. By using recent analysis, industry reports, and recognized journals, this paper highlights the current state of the discipline and potential development of the discipline. Among the most critical topics are safety, efficiency, cyber security, and technology integration, while newly available opportunities arise in fields such as artificial intelligence, machine learning, advanced communication systems, and sustainable aviation technologies. As an example, cognitive aeronautical communication radios will allow the radio system to adapt dynamically to the available spectrum resulting in increased communication efficiency as the demands for air traffic and technology increase (Jacob et al., 2016).

The paper also investigates the implications of system complexity growth for organizational design, with the implementation of digital transformation, embedded digital technologies, and advanced modeling tools to address integration, safety, and reliability (Lakemond et al., 2021). The paper also explores High Altitude Platform Station (HAPS) networks and their potential applications in aviation (Kurt et al., 2020), as well as sustainability assessments of emerging aircraft technologies, including battery-electric propulsion, alternative fuels, and more efficient air traffic management (Karabulut Kurt et al., 2021). Ultimately, the review confirms that reliability prediction methods in avionics are limited by traditional handbook-based methods and must be adjusted to ambient and operational conditions to achieve safety and performance of systems (Pandian et al., 2018).

As such, it is of tremendous importance for researchers, engineers, and decision-makers to integrate developments from a variety of disciplines, especially given the rapid pace of avionic system innovation. This paper meets that need by drawing on diverse but complementary sources to examine both present practices and future directions. The section below describes the method employed to select and synthesize the literature used to base this overall review.

Research Method

In its examination of developments and innovations within avionics systems, the article uses a narrative review approach. The review began with a systematic search of several scientific databases like Scopus, Web of Science, IEEE Xplore, ScienceDirect, and Google Scholar, in addition to curated conference proceedings, reports from industry organizations, and professional journals in aeronautics. Published material from the last decade received the most focus, but highly relevant foundational studies with longevity and significance were also included. The included studies were a reflection of core themes in current avionics, including communication systems, navigation systems, integration of unmanned vehicles, artificial intelligence, digitalization and sustainability, human factors, and reliability. Following the selection of these studies, they were read thoroughly, with each study's findings grouped into theme categories to establishing trends, highlight ongoing gaps, and examine possible areas of innovation. Along with trends in avionics systems, broader contextual considerations were also noted, including potential impacts of technological advancements on organizational arrangements for aviation; implications of technology on operational performance and safety; and predicted trajectories of avionics systems. By blending themes with context, the review provides a clear and flexible way to explain emerging trends and innovations in avionics.

Results and Discussion

Advancements in Communication, Navigation, and Surveillance (CNS)

CNS/ATM Technologies

Plans for improvements to increase capacity of both airspace and airports are meant to better utilize existing infrastructure and reduce delays (Sabatini, 2021). More accurate and reliable navigation and surveillance allow controllers to safely decrease separation between aircraft with more traffic density in the same airspace. The CNS/ATM system contributes to airport efficiency globally, spending less time occupying the runway for arrivals and departures. Despite the efficacy, there are benefits with intention and planning to integrate these technologies into current operations (Sabatini, 2021). These technologies aim to enhance airspace and airport capacity with greater efficiency of current resources, which will decrease delay (Sabatini, 2021). In conjunction with better navigation and surveillance, management will be able to safely optimize aircraft separation with more traffic density in the same airspace. It will increase airport efficiency due to reduced runway occupancy time and improved arrival and departure management. However, careful planning and coordination are necessary to achieve these potential benefits and realize their value in integration with the current operation (Sabatini, 2021).

Performance-based operations (PBO) are changing equipment requirements and operational standards by transitioning from prescriptive rules to criteria based on actual performance (Sabatini et al., 2020; Sabatini, 2021). Performance-Based Operations (PBO) value results that can be proven - safety, efficiency, and environmental performance - over following prescriptive processes or technology to achieve those results. It changes the focus from strictly adhering to prescriptive processes to achieving measurable operational benefits and allows for the development of new standards and regulations that provide guidance (Sabatini, 2021).

Cognitive Radio Applications

Cognitive radio systems enhance communications both between airframes and between airframes and ground stations by constantly monitoring the spectrum of radio frequencies and changing configurations in real-time to reduce interference and improve system performance (Sabatini et al., 2020; Sabatini, 2021). Cognitive radio systems also increase reliability and improve data rates while more efficiently using what little spectrum is available to meet increasing demand for air traffic and communications. Not only do cognitive radio systems increase the clarity of communication between pilots and controllers, they also increase the data rate of onboard system communications to allow for improved interaction between shared data. It is vital that even in the cognitive radio era, pilots be aware of, and follow, the standards of aviation communications to ensure that the modern communication systems for controllability, safety, interoperability, and trustiness (Sabatini, 2021).

High Altitude Platform Stations (HAPS)

High Altitude Platform Stations (HAPS) fly at an altitude of around 20 km which offers a broad communication coverage while avoiding many difficulties caused by weather (Kurt et al., 2020; Prysyazhnyuk & McGregor, 2022). For stratospheric operations, strong system design, management of thermal conditions, as well as environmental impact need to be considered. Developments in autonomous avionics and solar power have enabled HAPS to operate for long periods with minimal maintenance, making them a cost-effective solution for broadband, mobile, and emergency communications. They are also useful for urban use cases, such as air mobility, high-capacity data services, and public safety, but will need to be coordinated with airspace, spectrum, and regulatory planning (Kurt et al., 2020).

Unmanned Aircraft Systems (UAS) and Air Traffic Management (ATM)

Integration of UAS into Airspace

The rapid expansion of unmanned aircraft systems (UASs) is driving advancements in communications, navigation, and surveillance/air traffic management (CNS/ATM) technologies to allow for safe and effective integration into the established airspace (Sabatini et al. 2020). The existing air traffic management (ATM) systems were built for traditional manned aviation and do not support UASs and as a result, new technology, operating concepts, and airspace structures are needed. Reliable communication links and dedicated spectrum are critical for controlling UAS, transmitting data, and avoiding interference (Jacob et al., 2016). In urban areas, the reliance on real-time tracking, as well as high-density traffic management and defined airspace classes, is critical to ensuring the safety of UAS operation with manned aircraft in UAS Traffic Management (UTM) (Pongsakornsathien et al., 2020).

UTM and Performance-Based Operations

A performance-based airspace model helps manage UAS traffic by prioritizing results such as safety, efficiency, and environmental performance rather than rigid rules (Pongsakornsathien et al., 2020). This strategy provides operators with the ability to achieve performance targets through alternative technologies and procedures which encourages flexibility and innovation. This strategy also allows for adjustments to the use of airspace, navigation, and surveillance, as traffic situations change in real-time (Pongsakornsathien et al., 2020). Breaking airspace into sectors also helps with scalability and efficiency by balancing the communication needs and computational requirements.

Challenges in UAS Traffic Management

Integrating Unmanned Aerial Systems (UAS) within existing air traffic systems poses safety, operational flexibility, and infrastructure challenges and requires novel ideas to facilitate the UAS airspace integration process (Pongsakornsathien et al, 2020). Operations and tasks must establish that UAS operation presents no risk to manned aircraft and the people on the ground, with a variety of UAS types and flight profiles in mind. Existing air traffic system infrastructure may require alterations and upgrades to accommodate the UAS operations. Dedicated flight management is essential to allow the reduction of delays, enhance operational efficiencies, and reduce the expense of implementation, supported by algorithms and decision tools (Venkateswarlu et al., 2025). Furthermore, Urban Air Mobility (UAM) is increasing demands on the already crowded aviation spectrum and creates a need for cognitive radio, spectrum sharing, and modifications to previous assignment strategies to facilitate safe and effective urban airspace integration (Apaza et al., 2023).

Artificial Intelligence (AI) and Machine Learning (ML) in Avionics

AI in HAPS

Artificial Intelligence (AI) enhances HAPS operations by improving system design, resource allocation, and network management (Kurt et al., 2020). AI can also enable these platforms to operate more autonomously, predicting traffic patterns, modifying routes, and identifying issues—thereby lessening the intensity of human intervention (Kurt et al., 2020). In airspace management, AI assists with spectrum allocation and optimizing flight operation speeds for UAS by dynamically changing variables to improve throughput and lessen risks (Apaza et al., 2023). Furthermore, AI digital twins provide an opportunity for virtual representations of aircraft, airports, and air traffic systems that can be used to model, simulate performance, and conduct predictive modeling to improve efficiency, safety, and cost effectiveness to aviation operations (Barricelli et al., 2019).

Machine Learning for ATM

Machine learning is becoming a more significant component of Air Traffic Management (ATM) and will be leveraged to improve safety, efficiency, and decision-making (Sridhar et al., n.d.). Machine learning, in part, helps anticipate traffic, modify flight paths, alleviate congestion, and detect potential conflicts while also facilitating coordination among pilots, controllers, and airlines (Sridhar et al., n.d.; Giovanni et al., 2024). There are regulatory and certificating issues associated with airborne AI, and inherent cybersecurity risks of software faults, unauthorized access, and unknown interactions highlight the need for effective protections to sustain safe and reliable operations (Luettig et al., 2024; Kagalwalla & Churi, 2019).

Real-Time Flight Path Optimization

Real-time optimized flight paths could use machine learning to dynamically manage airspace, transitional states, and unanticipated disturbances resulting in improvements in safety, reductions in delays, and more efficient fuel management (Venkateswarlu et al., 2025). The systems would utilize information from radar, atmospheric sensor networks (profusers), and flight management systems to predict perturbation in flight and suggest changes of flight path, speed of flight, or altitude. Such solutions can use reinforcement learning techniques including Deep Q-Network (DQN) or Proximal Policy Optimization (PPO) to strengthen the learning and flight route decisions through trial and error, increasing safety, reliability and better style of flying in a complex airspace environment. (Venkateswarlu et al., 2025).

Digital Transformation and Complex Systems

Digital Integration and Complexity Management in Modern Avionics Systems

Modern avionics are increasingly combining digital technologies with physical systems, creating advanced cyber-physical platforms that improve control, performance, and safety, while also introducing new challenges in terms of complexity, security, and reliability (Lakemond et al., 2021). This digital shift is changing how avionics organizations are designed and how they innovate, requiring teamwork, knowledge sharing, and agile project management to take full advantage of tools such as cloud computing, big data analytics, and artificial intelligence (Lakemond et al., 2021). The transition from early analog systems to fully integrated digital platforms has also enabled advanced capabilities, including autonomous flight and real-time flight path optimization (Lakemond et al., 2021).

As avionics systems become more complicated, they can become unmanageable for one operator. Modeling and simulation tools facilitate understanding of system behavior and very large data sets (Lakemond et al., 2021). They provide shared reference points to help with team coordination (Lakemond et al., 2021). Safety also requires systems being capable of adapting in order to suspend and preserve necessary functionalities during unexpected situations (Lakemond et al., 2021). All of these efforts improve operator awareness and the safety of systems.

Digital Twins

Digital twins are virtual copies of physical systems powered by AI that allow for real-time monitoring, analysis, and optimization of intricate assets like aircraft (Barricelli et al., 2019). Through the fusion of diverse data from sensors, simulations, and operational history, they enable performance tracking, predictive maintenance, process optimization, and decision-making, driving efficiency, lowering costs, enhancing safety, and enabling training and product development (Perera & Noteboom, 2023). But with this integration of diverse data sources comes the cybersecurity issue, and strong mitigation is required to avoid unauthorized access, data breaches, and system tampering in aviation operations (Ukwandu et al., 2022). Generally speaking, digital twins offer a rich-data virtual space to enable thorough insight into system behavior and resolve monitoring issues that are hard to address directly.

Sustainability and Environmental Considerations

Emerging Aircraft Technologies

A growing awareness of aviation's influence on climate change has led to growing interest in aircraft technologies to reduce emissions and noise (Karabulut Kurt et al., 2021). Possible options include battery-electric propulsion, alternative fuels, and low-impact materials that may provide clean and quiet performance as compared to conventional jet engines. Battery-electric systems, specifically, are zero-emission during flight and are quieter, though range and payload are still restricted, requiring some improvements in battery technology. Life-cycle analyses (LCA) are critical to measure environmental hotspots and socio-economic challenges and achieve a proper picture of the sustainability influence of these new technologies (Karabulut Kurt et al., 2021).

Alternative Fuels and Energy Efficiency

Biofuels, synthetic fuels and hydrogen are integral components of sustainable aviation and can considerably contribute to overall net reductions in greenhouse gases from aviation activities (Karabulut Kurt et al., 2021). These fuels are produced from renewable feedstock including but not limited to biomass or algae and/or using solar energy. Nevertheless, these fuels continue to face challenges with respect to cost and cumbersome energy costs to produce, which typifies a requirement for efficient production.

Emerging propulsion systems, including battery based, fuel-cell-based and hybrid-electric systems, leverage combinations of technologies to improve efficiency while reducing emissions (Karabulut Kurt et al, 2021). For example, hybrid electric systems could employ electric motors during take-off and landing to reduce the amount of fuel consumed, or alternatively the new fuel-cell could theoretically achieve zero emissions by the use of fuel in the capacitor and oxygen from the atmosphere, respectively.

If available, with these technologies, aviation is better suited to move towards more sustainable and energy efficient approaches that reduce the environmental impacts of aviation and support sustainable air transportation into the future. The successful development and implementation of these technologies is premised on cross-sector involvement between government, industry, and researcher efforts (Karabulut Kurt et al., 2021).

Solar-Powered Aircraft

Solar-powered aircraft harness the energy of sunlight via photovoltaic (PV) solar panels coupled with battery systems that provide for long flying times and maximum power point trackers (MPPTs). PV solar panels capture sunlight, and MPPT tracks the system to maximize the energy value, while the battery allows for storage options and flight during the night or low-light conditions (Safyanu et al., 2019).

Furthermore, new photovoltaic innovations such as thin film and multi-junction cells are increasing the efficiency and the possible flight times of solar powered airplanes (Safyanu et al., 2019). Thin film solar cells offer weight savings and flexible designs while multi-junction solar cells can collect a much wider wavelength of sunlight to achieve increased solar values. Flight duration benefits from research in energy storage development, specifically lithium-air (Li-air) batteries, that are lighter and have a greater energy density than lithium-ion batteries for flight time. Li-air batteries are still in development but the value of this technology will prove to be enormous in sustainable aviation in the near future.

Human Factors and Ergonomics

Human-Machine Interaction

Unmanned systems differ from traditional ergonomics because it is no longer only about physical interface, but also about cognitive elements such as trust, awareness of the situation, and decision making. The digitization and physical distancing dilemma of automation also provides an ergonomic paradox: automation was designed to offer the benefits of improved performance and safety; however, this does not always translate to improved performance when promoting safety (Mygal & Protasenko, 2022). While highly automated systems may decrease human workload and human error, they may decrease an operator's situation awareness and degrade their skill as a performance gap may occur, or a gap in performance may be created out of trust in automated or unmanned systems. Automation and automation systems should ultimately be designed as systems that are resilient to human error while effectively allowing for the human oversight role (Mygal & Protasenko, 2022). Regardless, operating unmanned systems requires thinking about the human factors: workload, awareness of the situation, and decision making; ensuring a balance between understanding the benefits of unmanned systems while taking preventive measures to reduce new risks to every day safety and operational effectiveness.

Challenges in Unmanned Systems

Unmanned aerial vehicles (UAVs) pose unique human factor issues resulting from their remote operation and necessitating specific human factors designs, operator training and operational procedures (Mygal & Protasenko, 2022). Operators utilize both sensors and displays to remain cognizant of the operationally-relevant environment and make decisions pertinent to the flight. Therefore, it is vital to inform operator accountability by designing an interface with consideration of limits on perception or cognition. It will also be necessary to understand the causes for human error (i.e. fatigue, stressful conditions, inadequate training, or system design) so as to develop effective, and implementable risk mitigation and safety enhancement strategies. It is important to continually evaluate and inform practices in aviation to solve new safety challenges, that may not fit well with the standard assumptions used in frameworks and contemporary thinking around safety, linking this consideration of human factors with technological advances. Innovations designed to produce changes to the design of operations and working practices, in this context, improves safety in the aviation sector, while concurrently allowing for the adoption of high-risk UAV systems that are becoming increasingly autonomous and complex (Mygal & Protasenko, 2022).

Human Error Identification

New aviation concepts, like autonomous flight and urban air mobility, require new paradigms for human-machine interaction that proactively account for potential human errors (Irshad & Walsh, 2024). Established methods for addressing human error (i.e., accident investigation, etc.) only identify errors, and their impact, well after the error has occurred. Proactive methods—like human-in-the-loop simulations, cognitive task analysis, and upfront consideration of human factors during design activities—allow for an error to be anticipated and mitigated, prior to the operation of the system.

Methods of natural language processing (NLP) additionally provide a means of enhancing safety by using incident reports to analyze for patterns of errors or mechanisms underneath, which provides evidence-informed knowledge for improved system design (Irshad and Walsh, 2024). By considering human factors from the onset, systems will also facilitate interactions with increasingly automated and complex technologies within aviation.

Reliability and Safety

Reliability Prediction Techniques

Reliability is paramount in avionics systems where failure can result in catastrophic outcomes (Pandian et al., 2018). Many handbook-based methods suffer from limitations including outdated and irrelevant data, or failing to address the realities of modern, complex operational conditions. Other methods such as similarity analysis, testing, and physics-of-failure provide more accurate and holistic contrivances for assessing reliability, while considering operational conditions, system design, and materials, which will improve the safety and reliability of avionic systems (Pandian et al., 2018).

Enhancing System Safety

The National Academy of Sciences in the USA has deprecated the use of traditional reliability prediction using the Military Handbook (MIL-HDBK-217) approach and has called for new and updated methods (Pandian et al., 2018). Digital avionics systems pose new safety challenges, such as software errors, cyber security vulnerabilities, and inadvertent interactions between components, thus, robust cyber security measures must be in place to ensure flight safety and operational continuity (Kagalwalla & Churi, 2019; Mygal & Protasenko, 2022). Unmanned systems increase the challenges to safety and reliability requirements and therefore require innovative design, testing, and certification practices for effective functional performance in environments with little or no human access (Mygal & Protasenko, 2022).

Proximity Maps

Aircraft proximity maps, designed with data-driven flow modeling, improve safety through real-time visualization of aircraft positions, density of traffic and possible conflicts ("Aircraft Proximity Maps," 2024). Using a probability density function to evaluate inter-aircraft distances allows the maps to calculate measure aka numerical indications of the level of risk of collision. As a result, both air traffic controllers and pilots able to identifying opportunity for hazard mitigation and adjournment prior to an event occurring ("Aircraft Proximity Maps," 2024).

Design and Manufacturing Innovations

Additive Manufacturing

Metal additive manufacturing is changing aerospace manufacturing by helping develop complex, lightweight, and high-performance parts (Blakey-Milner et al., 2021). These advantages include decreased costs, material efficiency, innovative designs, and reduced components to create more sustainably efficient aircraft. Applications for metal additive manufacturing system include propellant tanks, liquid-fuel rocket engines, and heat exchangers for satellites, all of which demonstrate the breadth of applications for metal additive manufacturing and its advancements for aerospace (Blakey-Milner et al., 2021).

The GENUS Aircraft Design Framework

The GENUS Aircraft Design Framework addresses some of the shortcomings of traditional synthesis packages by taking a holistic, integrated approach to aircraft design (Smith et al., 2018). It enables designers to examine multiple design concepts, enhance performance in different disciplines, and utilize consistent prediction tools toward informed design and engineering decisions. Combining a variety of methods and optimization techniques, the framework delivers multiple levels of flexibility and adaptability, while remaining user-friendly for diverse users (Smith et al., 2018).

Shape Memory Vitrimers

Hot-pressing shape memory vitrimers promote multi-shape memory and multifunctionality allowing for smart materials that respond to external stimuli by adapting, self-healing, and performing multiple functions (Pei et al., 2015). These polymers may recover their original shapes, retain their structural integrity, and can create adaptive components for aircraft. The ability to reconfigure easily and produce these materials at scale provides opportunity to be utilized in the design of complex, customized and cost-effective smart structures (Pei et al., 2015).

Future Trends and Research Directions

Integration of Technologies

More advanced avionics systems will necessitate closer alignment of communication, navigation, and surveillance technologies as we transition to a more seamless and efficient way of managing air traffic (Sabatini et al., 2020). The incorporation of newly emerging technologies such as artificial intelligence and digital twins should allow us to create more autonomous, intelligent systems, and in turn, improve safety, efficiency and reliability (Barricelli et al., 2019). Additional studies should focus on the possibilities of synthesizing both current and established methods into a seamless response, establishing coordinated collaborations amongst researchers and industry for maximum effectiveness of the system (Karabulut Kurt et al., 2021).

Addressing Challenges

To satisfy the increase in air travel demand, we must manage both airspace congestion and limited spectrum availability while maintaining safe and efficient avionics functions (Jacob et al., 2016). Novel methods, and planning, for the management of unmanned systems will be needed to be able to safely allow unmanned into more complex operating environments alongside manned aircraft (Mygal & Protasenko, 2022). It is also important to resolve limitations to existing reliability predictions in order to develop avionics systems that are robust and fault tolerant and can identify potential issues early in the design process (Pandian et al., 2018).

Research Opportunities

To facilitate the safe and efficient development of UAM operations, research should continue toward the development of new frequency management processes (e.g., dynamic spectrum allocation and cognitive radio solutions) to improve spectrum utilization and reduce congestion (Apaza et al., 2023). Additionally, we should develop multi-objective optimization algorithms to improve trajectory planning that will reduce fuel consumption, delays, and improve passenger comfort while continuing to support Air Traffic Management (ATM) systems (Gardi et al., 2019). In addition, it is also important to conduct further investigations of human factors and error mechanisms to further enable user-centered design approaches of next generation avionics systems that enable increased usability, safety and efficiency (Irshad & Walsh, 2024). Overall, progress in these research areas will ultimately advance the safety, efficiency, and sustainability in aviation.

Conclusion

The current evolution of avionics is reshaping nearly every element of contemporary aviation, from aircraft communications and navigation to energy management, automation, and human–machine interactions. This review brings together research from several fields and shows how existing issues such as lack of spectrum, complexity of systems, cybersecurity problems, and sustainability are tied to new possibilities such as cognitive radio, AI-based decisions, digital twins, and advanced manufacturing.

Rather than consider these changes in isolation, it is apparent that the future of avionics will depend on integrating technology, operational concepts, and human issues. The addition of unmanned aircraft, new green propulsion, and predictive reliability is a sign we are converging around a model that supports an aviation system that is more interconnected, efficient, and resilient. At the same time, this raises critical questions about certification, interoperability, and the means and timing under which these systems merge safely.

This review demonstrates how the themes discussed in this review intersect, underscoring the need for continued collaboration among engineers, researchers, regulators, and industry partners. The next generation of avionics will not be characterized by one large, new innovation but by a careful integration of many innovations around systems that are connected and significant from a technical innovation perspective.

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