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Avionics Systems Panel Research and Innovation Perspectives

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INTRODUCTION

The Avionics Systems Panel (ASP) is a technical operations panel of the IEEE Aerospace and Electronics Systems Society (AESS). The panel addresses contemporary issues in avionics systems research, design, test, and certification for civil and military applications. Areas of focus include: communications; command and control; navigation; surveillance; manned/unmanned air traffic management (ATM) management; and space systems (launch vehicles, spacecraft, and satellites). The ASP monitors, analyzes, and supports industry and government activities relevant to its technical focus, such as the National Aeronautics and Space Administration (NASA) Unmanned Aircraft Systems (UAS) Traffic Management (UTM), the Federal Aviation Administration (FAA) Next Generation Air Transportation System (NextGen) program, and the European Union (EU) Single European Sky ATM Research (SESAR) program that impact the future of aviation. The high-level goals of the ASP include:

- to promote and support collaborative research initiatives in the domain of avionics;
- to promote and support collaborative research in the domain of UAS;
- to promote and support high-quality IEEE publications in the domain of avionics;
- to promote and support educational activities in the domain of avionics;
- to sustain and oversee the programs of the IEEE/AIAA Digital Avionics Systems Conference (DASC), the Integrated Communications Navigation and Surveillance (ICNS) Conference; and create new conferences or partnerships;
- to manage the nomination and selection of candidates for IEEE awards in the domain of avionics;
- to encourage nominations for IEEE Fellows and Senior Members in the domain of avionics;
- to recommend and support new IEEE Standards or revisions of existing IEEE Standards pertaining to the domain of avionics; and

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  - to establish a liaison and joint work programs with other relevant IEEE societies or professional societies on behalf of AESS to promote unmanned and intelligent systems technologies at current and new conferences.

Membership in the ASP is open to active IEEE members from the aerospace community who desire to advance avionics technology and system capabilities. Currently, the panel includes several standing committees, including: Avionics Research and Innovation (R&I) Committee; Avionics Conference Committee; Awards, Nominations, and Elections Committee; Standards Committee; Education Committee; Journal Publications Committee; UAV Panel Committee, and Cyber Security Panel Committee.

The ASP has a strategic agenda of initiatives liaising with national, regional, and international research organizations that are impacting the future of the aviation and aerospace sectors. The ASP develops and maintains a robust research cooperation program of work in collaboration with relevant industry and government organizations. In particular, the ASP activities in the avionics sector focus on the following areas, as also illustrated in Figure 1:

1) Communication, Navigation, and Surveillance for Air Traffic Management (CNS/ATM):
   - Evolution of the certification framework for integrated CNS and Avionics (CNS+A) systems;
   - civil and military airspace integration and CNS+A systems interoperability.
2) Avionics Systems Integration and Security:
   - fault-tolerant avionics design and integrated vehicle health management (IVHM) systems;
   - cyber-physical security of avionics and CNS/ATM systems.
3) Multidomain Avionics (MDA):
   - UAS integration in all classes of airspace and UTM;
   - avionics for future space transport, space traffic management (STM) and intelligent satellite systems.
4) Automation and Autonomy:
   - development of avionics human-machine interfaces and interactions (HMI^2); and
   - artificial intelligence (AI)/machine learning (ML) in avionics systems design and operations (including the challenges of certification and the role of explainable AI).

The ASP has a leading role in the organization of the DASC and ICNS Conferences. The latest editions (2016 to 2019) of these conferences have focused on UAS and civil–military airspace integration, such as the role of autonomy. Besides the traditional ATM framework, the recent proliferation of small UAS (sUAS) applications and the increasing interest in the potential of urban air mobility (UAM) has led to address the multidimensional challenge of the UAS integration in low-altitude environments. In fact, several research initiatives are currently underway worldwide to define safety thresholds and develop policies, procedures, and systems that would make UAS unrestricted airspace access a reality.

In parallel, progress in spaceflight research has led to the introduction of various manned and unmanned reusable space vehicle concepts, opening up uncharted opportunities for the emerging space transport industry. For

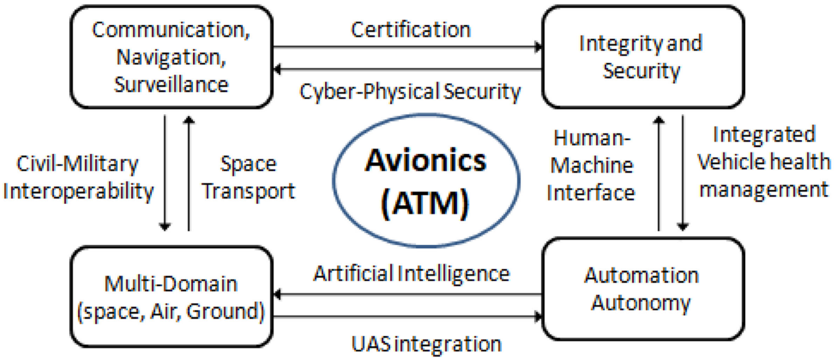

Figure 1.
Avionics sector—Four areas of focus.

future space transport operations to be technically and commercially viable, it is critical that an acceptable level of safety is provided, requiring the development of novel mission planning and decision support tools that utilize advanced CNS technologies and allow seamless integration of space operations in the current ATM network.

ASP has engaged in research to support the “Agility Prime” initiative for flying cars and electrical vertical take off and landing (eVTOL) aircraft systems and the NASA advanced air mobility (AAM) program to integrate manned and unmanned aircraft into U.S. airspace.

AVIONICS INDUSTRY OUTLOOK

The global avionics systems market is projected to exceed USD 94 billion by 2025 [1]. The global growth of avionics can be attributed to the rising demand for new aircraft from increasing passenger traffic and cargo movements, particularly in Asia Pacific, Middle East, and Africa. Significant advancements in digital technologies act as drivers for the market and increasing defense spending from countries such as India and China drive the demand for military avionics systems, further supporting the market growth. The increasing demand for lightweight and low-volume avionics systems for UAS is also contributing to the growth. Continuous rapid advances in airborne computing, sensors, and communication technologies are stimulating the development of integrated avionics systems for an increasing number of civil and military applications. Avionics companies are focusing on higher level of automation, including digital co-pilots/pilot assistants, airborne wireless network, and AI/ML technology to gain a competitive edge over rivals, while maintaining critical safety requirements. In particular, intelligent automation and networking technologies are being extensively applied to UAS and space platforms, allowing the development of high-performance multisensor guidance, navigation, and control (GNC) systems as well as advanced mission systems with reduced size, weight, power and cost (SWaP-C).

The widespread introduction of performance-based navigation (PBN) is the first step of an evolutionary process from equipment-based to performance-based operations (PBO). PBN specifies that aircraft navigation systems performance requirements shall be defined in terms of accuracy, integrity, availability, and continuity for the proposed operations in the context of a particular airspace when supported by an appropriate ATM infrastructure [2]. The full PBO paradigm shift requires the introduction of suitable metrics for performance-based communication (PBC) and performance-based surveillance (PBS). The proper development of such metrics and a detailed definition of PBN-PBC-PBS interrelationships for manned and unmanned aircraft operations represent one of the most exciting research challenges currently facing the avionics research community with major impacts on air transport safety, airspace capacity, and operational efficiency [3].

In parallel, the International Civil Aviation Organization (ICAO) Aviation System Block Upgrades (ASBU) rely on a progressive introduction of advanced CNS technologies, including digital data links, satellite services, and automatic dependent surveillance–broadcast (ADS-B), which will effectively enable the transition to network-centric aviation operations [4]. However, the international aviation community (both civil and military) is now facing important technological and operational challenges to allow a proper development and deployment of the CNS+A innovations announced by NextGen, SESAR, and other programs, such as the Collaborative Actions for Renovation of Air Traffic Systems (CARATS) in Japan and OneSky in Australia. In particular, it is essential to address global harmonization issues and to develop a cohesive certification framework for future CNS+A systems simultaneously addressing safety, security, and interoperability requirements as an integral part of the design, development, test, and evaluation (DDT&E) process [5]. Aviation avionics establishes nonprecession and precession approaches for airports with redundant equipment for flight safety. The global positioning system (GPS), Glonass and Galileo navigation systems have vulnerabilities to noise jamming and limited coverage that affect world aviation operations.

According to aviation market forecasts predating the Coronavirus Disease 2019 (COVID-19) pandemic, air traffic was expected to double by 2025 and quadruple by 2050 [6].Within the same timeframe, it was also expected that aviation would contribute 6% of all human-induced climate change [7], while half of all air traffic would take off, land, or transit through the Asia-Pacific [8]. While finalizing this article, the COVID-19 pandemic has led to a reduction in global air traffic in the order of 90%. However, once the emergency is resolved, it is reasonable to assume that both domestic and international air travel will return to prepandemic levels. If this assumption proves correct, the market forecasts in [6]–[8] may be a bit delayed but are still acceptable in the long term.

Personnel costs already account for a large portion of air navigation service provider (ANSP) and airline expenditures, while schedule predictability and flight delays are growing problems with significant direct and opportunity costs to national economies. Additionally, the proliferation of remotely piloted/autonomous vehicles for atmospheric flight and the concurrent development of reusable space transportation systems are expected to pose their own challenges and produce significant impacts on ATM operations with clear consequences on both human–machine systems and infrastructure to support highly automated, resilient, and "trusted autonomous" air-and-space operations.

In response to these challenges, modern avionics systems are becoming cyber-physical, with software and hardware components seamlessly integrated toward performing highly automated/autonomous tasks. These tasks are progressively more demanding and distributed among multiple platforms/subsystems, while recent research trends elicit the introduction of AI, fault-tolerant architectures, and adaptive HMI^2 to support the development of trusted autonomous systems (TAS).

GLOBAL RESEARCH PROGRAMS

The continuous growth of civil air transport and the widespread adoption of UAS for new and traditional roles pose significant challenges to the aviation community, as the current on-board and ground-based systems will not ensure the desired levels of safety, efficiency, and environmental sustainability in future airspace operations. As a consequence, several large-scale R&D initiatives were launched over the last two decades. Current programs are investigating the most promising technology and operational improvements to enhance the levels of safety, capacity, efficiency, and environmental sustainability associated with current and likely future air transport in a holistic manner by improving the design, manufacturing, operation, and lifecycle management of aircraft. In the avionics domain, significant progresses in terms of safety, capacity, and efficiency of air traffic are expected from the implementation of novel CNS+A concepts and technologies by NextGen, SESAR, CARATS, and other programs [9]–[11]. Comprehensively, these current international programs support the evolution of ATM into a highly automated, integrated, and more collaborative system, allowing a more flexible and efficient management of the airspace and airport resources through higher levels of automation and more accurate navigation to maximize capacity. The ICAO's ASBU framework builds upon these major air navigation improvement programs, aiming to drive a harmonized evolution of the overall CNS+A system capabilities. An ASBU block consists of several modules, each relating targeted operational improvements with the governing standards, procedures, technology, and equipage required to implement them.

Several concepts were proposed as part of the major ongoing avionics and ATM modernization programs. The concepts are normally classified based on their relevance for en-route operations, terminal maneuvering area (TMA) operations, airport operations, and on the network. Increasingly higher amounts of information are being collected, analyzed, and shared among ground-based ATM and airborne avionic systems to more effectively deal with unpredicted events and mitigate disruptions. In order to optimally exploit these quickly growing amounts of information, an increase in automation support and a move away from the centralized command and control (C2) oriented ATM paradigm toward more distributed/collaborative planning are necessary.

Collaborative planning involves creation of new services and redistribution of current ATM functions to other key players such as airline operation centers (AOC) and avionics systems in order to improve the efficiency and safety of the system as a whole. In summary, the key CNS+A advances identified by the major modernization programs around the globe include [11]:

Four-dimensional trajectory (4DT) based operations:

- higher levels of collaborative decision making (CDM) to allow all involved parties to participate in the enhancement of system performance by sharing and accessing more accurate and updated information;
- role shifting of ATM from C2 oriented units to a highly automated, intelligent, and collaborative decision maker in an interoperable network-centric environment;
- dynamic airspace management (DAM) for an optimized exploitation of airspace capacity;
- improved avionics and ATM systems HMI^2 design, interoperability, and higher levels of automation;

- performance-based CNS, enabling PBO. ATM digital communication between the airspace controller and the aircraft pilot for improved safety avoiding cockpit overload and misinformation errors.

In order to introduce these innovative concepts and ultimately progress along the planned evolutionary pathways, a number of new CNS+A technologies are considered essential, including:

- avionics and ATM decision support systems (DSS) featuring automation-assisted 4DT planning and negotiation/validation functionalities;
- enhanced visual line-of-sight (VLOS) and beyond VLOS (BVLOS) communications, including a substantial exploitation of ground-based and satellite-based aeronautical data-link technology;
- enhanced navigation accuracy and integrity by means of ground-, aircraft- and satellite-based augmentation systems (GBAS/ABAS/SBAS), promoting dual-frequency/multi-constellation global navigation satellite systems (GNSS) as primary means of navigation; as well as alternative position navigation and timing (APNT) systems as backup for GNSS.
- enhanced ground-based and satellite-based surveillance, including ADS-B, multilateration (MLAT), and other self-separation services;
- advanced sensor systems with data fusion, real-time analytics and learning to enable autonomy; and
- a system wide information management (SWIM) network.

In order to be economically and operationally viable, these novel CNS+A technologies and operational concepts must be developed and deployed in a phased manner. The stages for such evolution within SESAR were defined based on the capability and consist of [10]:

- *Time-based operations:* Operations for which strategic and tactical ATM and air traffic flow management (ATFM) actions are aimed at optimal traffic synchronization. The time of arrival of traffic at specific points is the fundamental metric being estimated, managed, and monitored by all the involved entities (ground-based and airborne).
- *Trajectory-based operations (TBO):* Operations focusing on evolution of predictability, flexibility, and environmental sustainability of air traffic resulting in additional capacity. This stage involves the evolution of the legacy flight plans into dynamically managed 4DT, which become the continuously updated and negotiated reference plan for the aircraft mission.
- *Performance-based operations (PBO):* Operations for which all the available CNS performance is exploited to establish a high-performance, network-centric, collaborative, integrated, and seamless ATM system, supporting high-density air traffic. In this stage, ATM services are customized depending on the highest level of CNS performance provided by the involved traffic and ground systems, enabling a further enhanced exploitation of airspace capacity.

TBO are based on the adoption of 4DT defining the aircraft's flight path in three spatial dimensions (i.e., latitude, longitude, and altitude) and in time from origin to destination and on the associated precise estimation and correction of current and predicted traffic positions. Each aircraft is assigned a 4DT contract, which is determined by means of a collaborative decision making (CDM) process involving novel ground-based and airborne DSS, evolving from the original reference business trajectory. Increased efficiency and higher throughput are obtained in a CNS+A context by actively managing 4DT. So, TBO is essentially a combined gate-to-gate spacing and trajectory optimization approach specifying aircraft trajectories in four dimensions. Next, generation air traffic management (NG-ATM) systems with automated 4DT functionalities will require advanced software architectures with automated trajectory negotiation algorithms. These will allow ground-based ATM systems to work in combination (and largely autonomously) with next generation flight management systems (NG-FMS) to generate optimized trajectories based on multiple criteria including real-time changes to the operational environment. The connectivity results in a highly automated process, where 4DT intents are validated through real-time negotiation, ensuring adequate separation between aircraft and maximizing efficiency in the use of the airspace resources. An essential infrastructure required to support this concept is the next generation aeronautical data link (NG-ADL). Initial 4DT (i4DT) operations are estimated to develop toward full 4DT implementation in 2028 [10]. The overall concept is illustrated in Figure 2.

In the PBO context, the ATM services will be matched to the performance capability of aircraft, navigation avionics, and aircrew. Airlines deploying PBO-capable equipment will benefit from easier access to congested areas and time periods. The regulations will impose requirements in terms of system performance rather than in terms of specific technology or equipment. Some of these CNS+A technologies are already approaching the market, while early stage advancements in the regulatory framework are accommodating enhanced operational capabilities. Since most of the innovations currently being implemented were conceived from the operational point of view, the concurrent development of an adequate theoretical framework and the execution of extensive modeling and simulation activities are crucial.

ICAO has authorized a globally coordinated plan published as the global air navigation plan (GANP) [4], to guide the harmonized implementation of CNS+A enhancements across regions and states. In the CNS+A context, aircraft safety is a shared responsibility between airborne and ground resources. Hence, air-to-ground communication is a safety challenge requiring changes to the current regulatory framework to properly capture the nature of this shared responsibility and the concept of "integrated" CNS+A systems. Certification of aircraft and ground equipment (hardware and software) together with organizational approvals is essential elements to ensure continued and enhanced safety. Certification also facilitates harmonization and interoperability of CNS+A systems across regions, subregions, and states. Furthermore, while new ATM and avionics technologies bring with them an increased level of automation, certification would be the instrument to ensure the safe and effective introduction of these technologies to achieve their full potential benefits. The aviation regulatory framework enforces and drives the certification process, while industry standards provide a vital link by offering methods of compliance for certification. The current certification framework for CNS+A is evolving, and it is required to keep pace with the global modernization efforts to ensure safety and sustainability of future aviation.

The ICAO GANP describes a strategic air transport modernization plan covering a 15-year period (2016–2030) that leverages existing technology and future developments based on industry agreed objectives and states' operational requirements. To move toward regional and national planning, the GANP includes the Aviation System Block Upgrade (ASBU), which is a consensus-driven systems engineering modernization strategy. The various ASBU modules and associated technology roadmaps cover communications, surveillance, navigation, information management, and avionics. The consistent application of those ASBU modules and blocks by the regions, subregions, and ICAO States will help achieve harmonization and interoperability. The blocks are availability time lines for a group of performance improvements. Each block spanning a period of five years is composed of modules, which include technological and procedural requirements for each of the four main areas of performance improvement, namely [2], [4]:

- airport operations;
- globally interoperable systems and data;
- optimum capacity and flexible flights; and
- efficient flight paths.

The sixth edition of the GANP [4] consists of a new multilayer structure with the following levels:

- *Global strategic level:* providing high-level strategic direction consisting of a common vision, global performance ambitions, and a conceptual roadmap.
- *Global Technical Level:* a basic building blocks (bbb) framework is defined in parallel to the ASBU. The BBB specifies minimum air navigation services for international civil aviation, as opposed to the ASBU that is performance driven [4], [12]. Basic services are aerodrome operations, CNS, air traffic management, meteorology, search and rescue, and aeronautical information. Another technical focus is a performance-based decision making method for defining implementation strategies.
- *Regional Level:* addressing regional and subregional needs aligned with the global objectives.
- *National Level:* focusing on national plans and deployment implementation and coordination.

With this structure, the main goal of the GANP is first to provide global strategic guidelines for the evolution of the air navigation system through the promotion of investment in innovation by means of R&D activities and the alignment of regional R&D programs. Second, to support the Global Technical Level implementation by ensuring the BBB foundation, facilitating the evolution of the ASBU framework and the optimization of air navigation resources with the performance-based decision-making method [11], [12].

Present day ATM is mostly a ground-based service with an overarching mission to prevent aircraft collisions and promote the orderly and expeditious flow of air traffic. ATM services are provided worldwide by a large number of ANSP and air traffic service organizations (ATSO) each with specific portions of airspace allocated under international agreements. ATM encompasses all systems and services that assist aircraft in safely accomplishing all their flight phases, including aeronautical meteorology, air navigation infrastructure, airspace management (ASM), air traffic services (ATS), and ATFM or air traffic flow and capacity management (ATFCM). On board aircraft advanced collision avoidance systems (ACAS) provide traffic advisory (TA) and resolution advisory (RA) when minimum aircraft separation is violated.

CNS+A technology is developing quickly and the regulatory framework that keeps pace is required. For global harmonization and interoperability, the required performance levels of CNS+A systems should be standardized across all classes of airspace. In the aviation context, standardization is enforced through certification, and the need for a cohesive CNS+A certification framework is to be

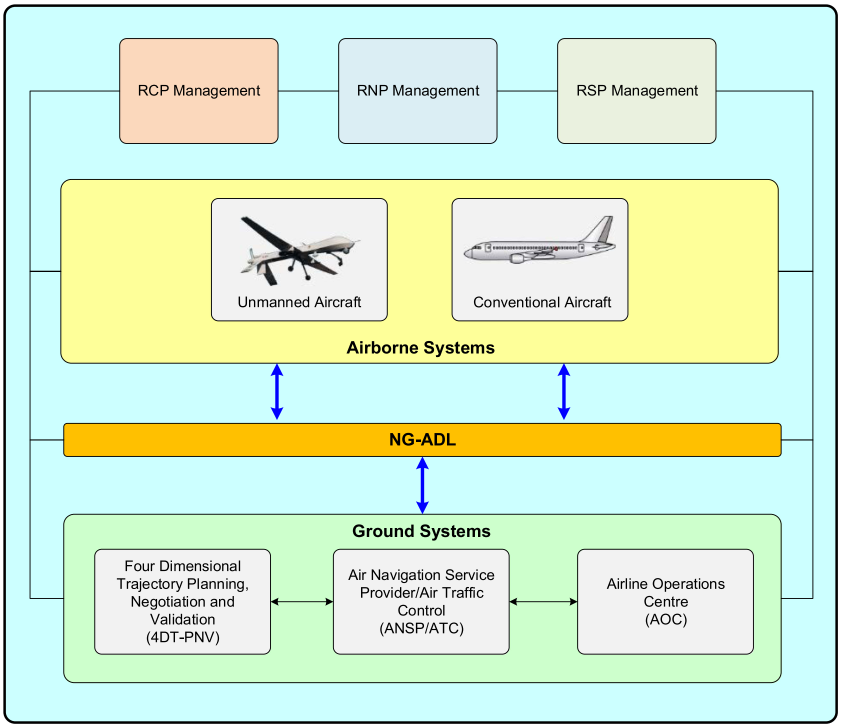

Figure 2.
CNS+A system architecture [3], [5].

stipulated through international and national regulations. Therefore, new safety considerations are to be embedded into aviation system life cycle processes to address the integrated nature of CNS+A systems.

Several aircraft accidents and incidents have occurred due to malfunctions of equipment hardware and/or software in both airborne and ground ATM equipment in addition to human error. In 2014 alone, three of these accidents resulted in hull loss claiming 517 lives [13]. In Europe, ATM was ranked second for the number of accidents and serious incidents by occurrence category in the period 2005–2015. This emphasizes the need for continuous improvements in safety in the face of traffic growth and the consequent emergence of advanced ATM concepts. The use of unproven new technologies and increased dependence on software with higher levels of automation and the growing interconnectivity among airborne, ground, and satellite systems (with shared responsibilities) results in a highly coupled and complex system of systems that demands more focus on safety during the design and development of ATM concepts [11].

Traditional ATM design has had a primary focus on demonstrating adequate levels of safety by performing analysis based on conventional (and largely separated) hardware and software assessment methodologies. This could be a costly and suboptimal approach, especially when requirements for enhanced capacity are to be simultaneously addressed. A more effective approach would be to design ATM systems that are inherently safe at the required capacity levels [15]. Safety is the critical consideration in the CNS+A design, development, test, and evaluation. Safety considerations must be an integral part of requirements development and the conceptual design of integrated CNS+A systems. Safety evaluation should be performed continuously from the early stages of CNS+A systems design and address all potential paths leading to either random or systemic failures. Systemic failures are more difficult to address since they are typically related to a combination of undetected technical and operational deficiencies. For example, recommendations from the investigation of the Uberlingen accident [16] (an acknowledged systemic failure) addressed the licensing procedures for ANSP staff, the certification process for technical facilities, and improvements to corporate culture, training, and risk management. More recently, the two consecutive Boeing 737 MAX 8 accidents occurred in October 2018 and March 2019 showed that increasing reliance on automation and autonomy requires a pragmatic rethinking of current test, evaluation, and certification standards for avionics systems. The Boeing 737 Maneuvering Characteristics Augmentation System (MCAS) crashes resulted in 346 deaths, 189 on Lion Air Flight 610, and 157 on Ethiopian Airlines Flight 302. The MCAS design was rushed and aircrew training was inadequate. Boeing has redesigned the MCAS and is in the process of recertifying the 737 aircraft.

CYBER-PHYSICAL SYSTEMS EVOLUTIONS

Avionics and ATM system architectures have become increasingly more complex, with the widespread adoption of heterogeneous sensor networks and the need for optimization algorithms that deal with a large amount of input data (including unstructured, semistructured, and asynchronous data), multiple objectives, and constraints. A well-known side effect of this complexity is the reduction or loss of situational awareness of the human operator, who is no longer capable of evaluating the validity and quality of the solutions implemented. Second, most of the automation being introduced is deterministic and lacks adaptability. Paradoxically, in certain scenarios, it may end up by increasing, rather than alleviating, the workload of human operators. Hence, instances of cognitive overload are not infrequent despite dealing with highly automated systems. Finally, the kind of automation that is currently being adopted in complex systems is not deeply trusted by humans because it lacks sufficient transparency and/or integrity [17].

It is therefore essential to develop new system architectures that address these fundamental challenges by implementing innovative cognitive processing and machine learning techniques toward enhancing human–machine interactions and building trusted autonomy. cyber-physical systems (CPS) are at the core of the digital innovation that is transforming our world and redefining the way we interact with intelligent machines. Present-day CPS integrates computation and physical processes to perform a variety of mission-essential or safety-critical tasks. From a historical perspective CPS combine elements of cybernetics, mechatronics, control theory, systems engineering, embedded systems, sensor networks, distributed control, and communications. Aviation safety is only assured by coordinated actions between the ATM and the aircraft aircrew or remote pilot for UAS. Man in the loop will remain a requirement to avoid serious hazards for the foreseeable future.

Properly engineered CPS relies on the seamless integration of digital and physical components with the possibility of including human interactions. CPS requires three fundamental functions to be present: control, computation, and communication [17], [18]. Practical CPS typically combine sensor networks and embedded computing to monitor and control physical processes, with feedback loops that allow physical processes to affect computations and vice-versa. Despite the significant progress in CPS research, the full economic, social, and environmental benefits associated with such systems are far from being fully realized. Major investments are being made worldwide to develop CPS for an increasing number of engineering applications, including aerospace, transport, defense, robotics, communications, security, energy, medical, smart agriculture, humanitarian, etc., [18].

Current avionics systems research is focusing on two main categories of CPS: Autonomous cyber-physical (ACP) systems and cyber-physical-human (CPH) systems. ACP systems operate without the need for human intervention or control. For ACP systems to work, formal reasoning is required as these systems are normally used to accomplish mission/safety-critical tasks and any deviation from the intended behavior may have significant implications on human health, well-being, economy, etc. A subclass is that of semi-autonomous cyber-physical (S-ACP) systems, which perform autonomous tasks in a specific set of predefined conditions but require a human operator otherwise. In contrast, CPH systems are a particular class of CPS where the interaction between the dynamics of the system and the cyber elements of its operation can be influenced by the human operator and the interaction between these three elements is regulated to meet specific objectives. CPH systems consist of three main components: physical elements sensing and modeling the environment, the systems to be controlled and the human operators; cyber elements including the communication links and software; and human operators who partially monitor the operation of the system and can intervene if and when needed.

Today, several aerospace CPS implementations are S-ACP systems. Semi-autonomous limits the achievable benefits and the range of possible applications due to the reduced fault-tolerance and the inability of S-ACP to dynamically adapt in response to external stimuli. Many S-ACP architectures are progressively evolving to become either ACP or CHP depending on the specific applications. Current research in the aerospace, defense, and transport sectors aims at developing robust and fault-tolerant ACP and CPH system architectures that ensure trusted autonomous operations with the given hardware constraints, despite the uncertainties in physical processes, the limited predictability of environmental conditions, the variability of mission requirements (especially in congested or contested scenarios), and the possibility of both cyber and human errors. A key point in these advanced CPS is the control of physical processes from the monitoring of variables and the use of computational intelligence to obtain a deep knowledge of the monitored environment, thus providing timely and more accurate decisions and actions. The growing interconnection of physical and digital elements, and the introduction of highly sophisticated and efficient AI techniques, has led to a new generation of CPS, that is referred to as intelligent (or smart) CPS (iCPS).

The demands of the “fourth industrial revolution,” also known as Industry 4.0, push the boundaries of iCPS to offer a broad range of opportunities for the development of novel avionics systems and services. Industry 4.0 focuses on new technologies to deeply connect the digital world with the physical world. Current trends with clear avionics applications include:

- advances in automation and autonomy;
- enhanced human–machine and machine–machine communications; and
- widespread adoption of artificial intelligence and machine learning.

Four key technology drivers enable these trends:

- big data and Internet of Things (IoT);
- advances in sensor networking and data analytics;
- improvements in transferring digital instructions to the physical world; and
- new forms of human–machine interaction, such as cognitive, augmented, and virtual reality systems.

By equipping physical objects with interfaces to the virtual world and incorporating intelligent mechanisms to leverage collaboration between these objects, the boundaries between the physical and virtual worlds become blurred [19], [20]. Interactions occurring in the physical world are capable of changing the processing behavior in the virtual world, a causal relationship that can be used for the constant improvement of processes [20], [21]. Intelligent, self-aware, self-managing, and self-configuring systems can be built to improve the quality of processes across a variety of application domains [21], [22]. Future advances in iCPS research are expected to accelerate the introduction of intelligent automation in avionics systems (both on manned/unmanned platforms and ground control systems) and to facilitate a transition to trusted autonomous operations. Major benefits of these capabilities include a progressive decrewing of flight decks and ground control centers as well as the safe and efficient operations of air and space platforms in a shared, unsegregated environment.

In the commercial aviation context, iCPS evolutions can support a transition from the current two-pilot flight crews to single pilot operations, with the copilot potentially replaced by a digital "pilot assistant" and/or a remote pilot on the ground [23], [24]. A single remote pilot on the ground, on the other hand, will no longer be restricted to controlling a single UAS and instead will be allowed to control multiple vehicles, in line with the so-called one-to-many (OTM) concept [25].

Important efforts are being devoted to the integration of UAS in all classes of airspace, eliciting the introduction of UAS Traffic Management (UTM) services seamlessly integrated with the existing (and evolving) ATM framework. In particular, UTM requires substantial advances in CNS+A technologies and associated regulatory frameworks, especially to enable low altitude and BLOS operations. Recent advances in communications, navigation, and sense-and-avoid (SAA) technology are therefore progressively supporting UTM operations in medium-to-high density operational environments, including urban environments.

Important research efforts are also ongoing to demonstrate the feasibility of avionics and CNS+A technologies capable of contributing to the emission reduction targets set by the International Civil Aviation Organization (ICAO), national governments, and various large-scale international research initiatives. Therefore, growing emphasis is now being placed on environmental performance enhancements, focusing on ATFM, dynamic airspace management, 4DT optimization, airport automation and, in the near future, urban flight operations.

As a consequence of these evolutions, future CNS+A systems will be widely interleaved, interconnected, and integrated. Therefore, such systems will have to meet more stringent requirements in terms of safety, integrity, interoperability, and CPS security. Theoretically these CNS+A systems will be interoperable across regions/states, between A/G systems and, possibly, between civil and military users. The use of ontologies concepts as a bridge for data sharing and interoperability is being researched, which would also support coordination of standards and mandates [26]. Cooperation between states is important to support the harmonization of the mandates and to achieve interoperability [5], [27]. The verification, validation, and certification of individual components as well as the "integrated" CNS+A systems capable of intent-based operations (IBO)/TBO are crucial for future systems. At present, standards and regulations are in place for the certification of individual components of the system with more focus on the airborne systems than the ground-based systems. These standards need to be reviewed for their adequacies in the context of complex integrated CNS+A systems. Furthermore, the requirement for ground system certification is not mandated by regulation in the same context as for airborne systems.

Certification requirements for the organizations engaged in aircraft and component design, production, maintenance, and crew/maintenance personnel training are well established in the European Union Aviation Safety Agency (EASA) and FAA regulations, together with the licensing requirements of pilots and aircraft maintenance personnel. Continuing airworthiness management requirements are well written into the regulations for large transport aircraft. However, airworthiness is currently not a requirement for sUAS, certain light aircraft and various experimental aircraft (including air mobility vehicles prototypes) that share airspace with manned aircraft. This is an important gap currently being addressed by both researchers and regulators, especially looking at the current evolutions of the UTM and UAM concepts. Additionally, it is commonly accepted that adequate regulations should be developed for evolutionary ATM/UTM system

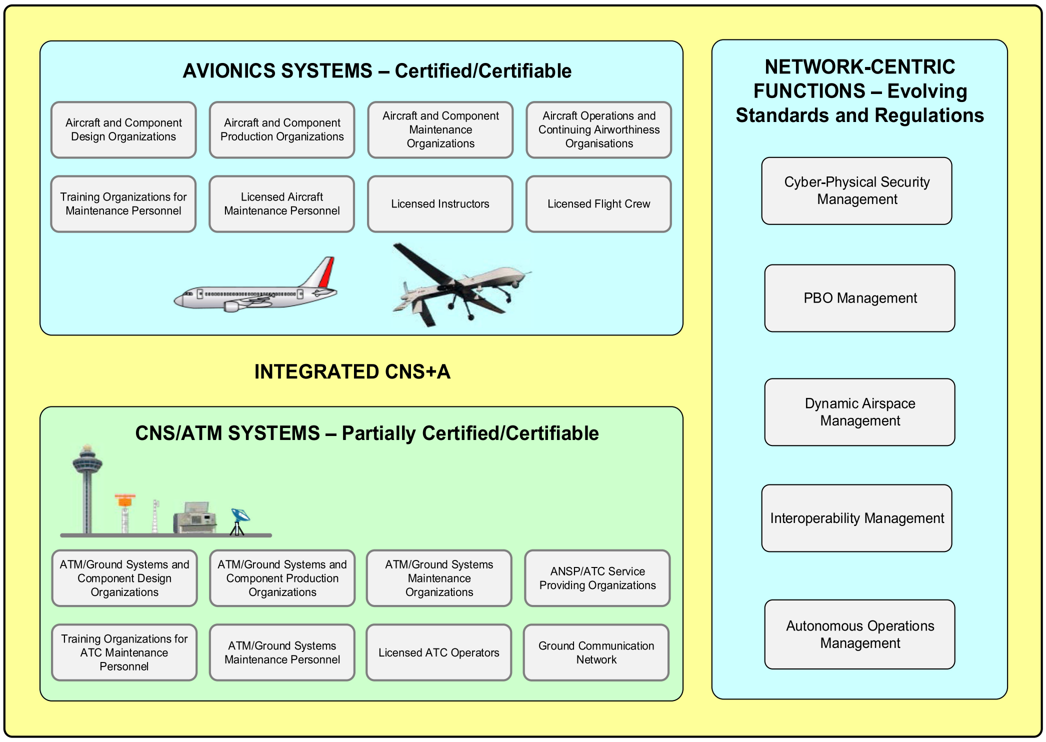

Figure 3.
Certification challenges of CNS+A systems [5], [28].

design, certification, production, and life cycle management. Current regulations that require organizational approval or certification of aerodrome service providers and ANSPs as organizations only partially fulfill the certification requirements of ground navigational aids, surveillance, and ATM systems. The responsibility for commissioning certification of ground systems is entrusted to the ANSP organization. In contrast, the civil aviation authority undertakes the responsibility of design certification of aircraft while the regulation authority is responsible for the issuance of the certificate of airworthiness of aircraft and also the oversight of the continuing airworthiness management of aircraft.

With regards to personnel licensing, regulation requires flight crew, aircraft maintenance technicians/engineers, air traffic controllers, flight operation offices/dispatchers, and aeronautical station operators to obtain a license issued by the regulator in accordance with ICAO Annex 1. While some states require ground navigational aids and ATM system maintenance personnel to obtain a company approval certificate, this is not equivalent to the licensing process of aircraft maintenance technicians and engineers. Furthermore, regulations do not mandate the licensing of design and maintenance personnel for ground systems. The current certification status of CNS+A key elements is illustrated in Figure 3, which indicates the airborne component of CNS+A as fully certified and the ground segment as not certified to the same level.

The CNS+A aircraft system specifications are currently based on regional requirements. Future harmonization, interoperability, and seamless operation require a global consensus to be provided for the equipment/system mandates through ICAO annexes and a progressive evolution of the applicable industry standards. A top-down systems engineering approach is recommended for the development of the certification model for integrated CNS+A [5].

In addition to CNS+A technologies for air operations, space avionics systems are also being researched and developed for a wide range of practical applications including commercial satellites, space transport/tourism, and interplanetary scientific missions. In this context, it is anticipated that economically viable and reliable cyber-physical systems will play a fundamental role in the successful development of the space sector and significant research efforts are needed in the field of reusable space transportation systems, space traffic management (STM), and intelligent satellite systems (SmartSats). In particular, the operation of space launch and re-entry platforms currently requires considerable airspace segregation provisions, which, if continued will become increasingly disruptive to civil air traffic. Moreover, the currently limited space situational awareness is posing significant challenges to the safety and sustainability of spaceflight due to the rapidly growing amount of resident space objects and particularly orbital debris [29]. The deployment of

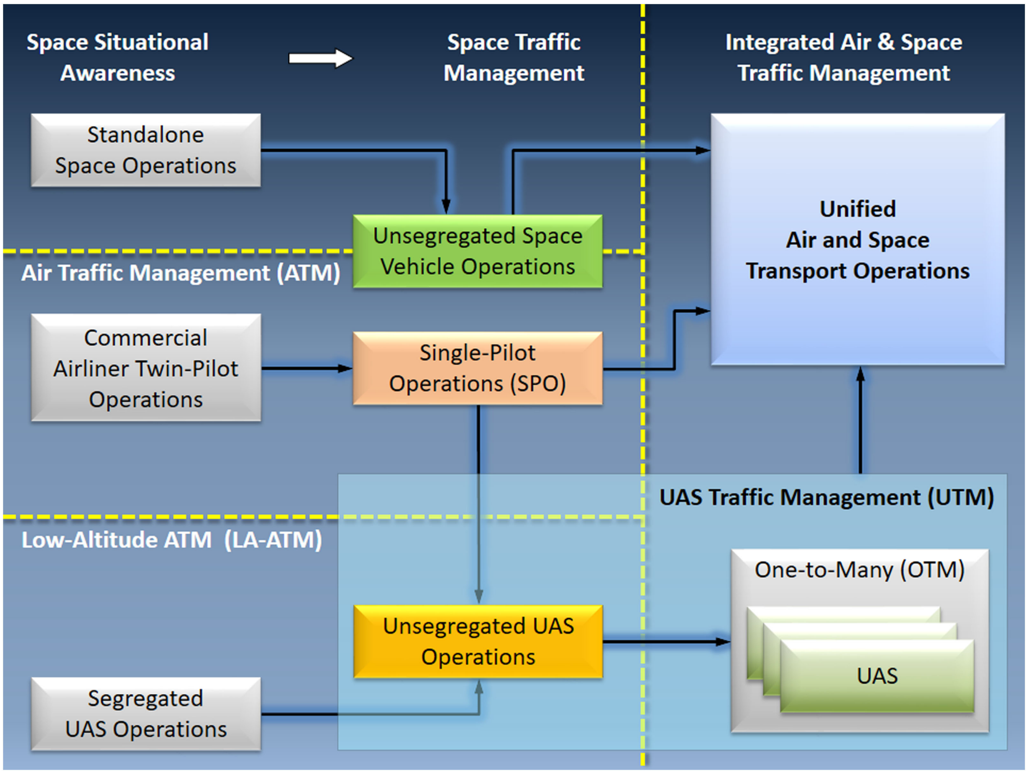

Figure 4.
Evolution and progressive integration of conventional and autonomous air and space platforms in a unified air-and-space traffic management framework. Adapted from [30].

network-centric CNS+A systems and their functional integration with ground-based ATM in a STM framework will support a much more flexible and efficient use of the airspace with higher levels of safety. As illustrated in Figure 4, these evolutions will support the progressive transition to what the research community has started designating as multidomain traffic management (MDTM).

In this context, there seems to be little doubt that AI/ML in particular will be key enablers of future highly automated and resilient air/space operations [31]. However, despite the numerous AI/ML techniques currently available and emerging, there are several key aspects that must be investigated before these technologies can be deployed operationally to avionics and CNS/ATM systems. Such aspects include vendor verification, regulatory certification, and end-user acceptance [32].

In particular, research is needed in the field of explainable AI (XAI) and computer-aided verification to keep pace with applied AI research and close the research gaps that could hinder operational deployment. Furthermore, it is expected that advances in XAI and associated systems/software engineering tools will further support the ongoing evolutions of the certification framework for CNS+A systems [5], [32].

Technological advances in avionics systems for aeronautical and space applications are eliciting the introduction of progressively more integrated and automated HMI^2. Contemporary HMI^2 evolutions address both manned and unmanned aircraft (fixed and rotary wing) and spacecraft specificities for the most fundamental flight tasks: aviate, navigate, communicate, and manage. Due to the large variability in mission requirements, greater emphasis is given to safety-critical displays and C2 functions as well as associated technology developments.

UAS mission-essential functionalities include planning and real-time decision support for aircraft operations. While current displays are able to integrate and fuse information from several sources to perform a range of different functions, these displays have limited adaptability. Important recent achievements include the operational deployment of synthetic vision and augmented reality (AR) technologies, which provide notable enhancements in safety and efficiency, particularly in terms of situational awareness [33], [34].

Further developments to increase HMI^2 adaptiveness have significant potential to enhance the on-board and ground human operator's effectiveness, thereby contributing to safer and more efficient air/space operations. Because of interface improvements, an increasing share of the avionics HMI^2 research is looking at adaptive display formats and functions [34], [35]. Emerging adaptive HMI^2

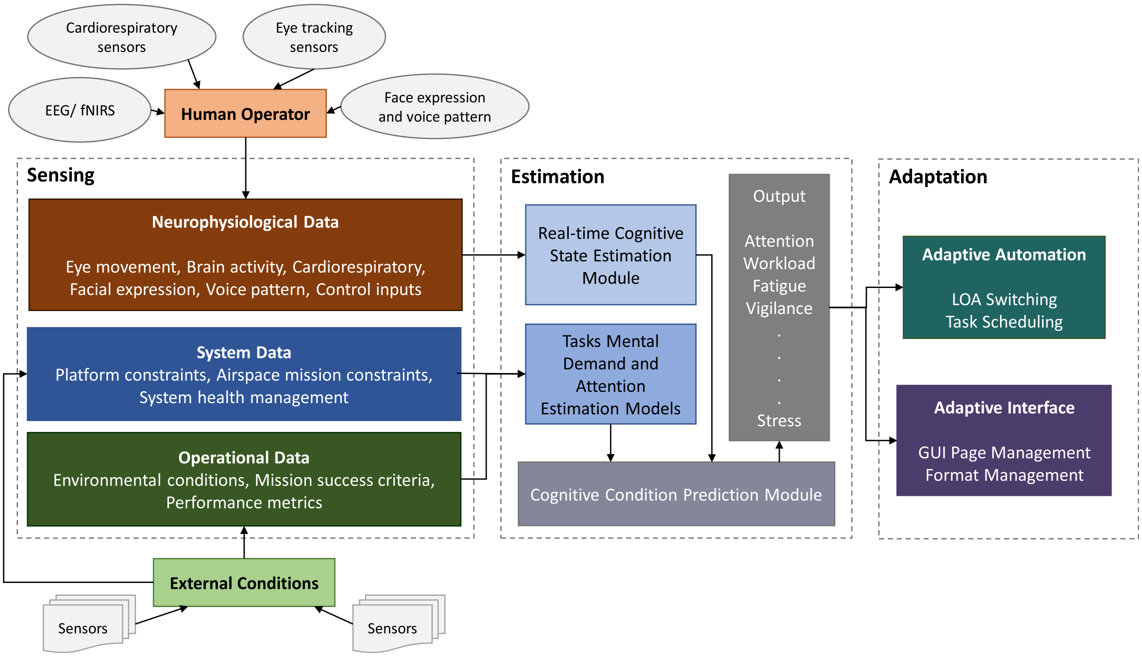

Figure 5.
Concept of cognitive HMI^2 for avionics systems [30].

concepts in the literature contain three common elements (see Figure 5): the ability to assess the system and environmental *sensing* states; the ability to access the *estimation* of operator states; and the ability to *adapt* the HMI^2 according to user needs [36]. While still an emerging area of research, HMI^2 adaptation driven by human performance and cognition has the potential to greatly enhance human–machine teaming through varying the system support according to the user's needs. However, one of the outstanding challenges in the design of such adaptive systems is the development of suitable models and algorithms to describe human performance and cognitive states based on real-time sensor measurements [30].

Integrated vehicle health management (IVHM) systems are primarily responsible for diagnostics, prognostics, and risk mitigation across both air and space platforms to support the replacement of failed or near failure components. They comprise of a set of hardware and software components as well as operational and maintenance processes that work together to ensure that the vehicle performs according to its specifications without unexpected failures. However, traditional IVHM systems lack the capability to provide real-time responses to detect, diagnose, and modify faulty vehicle subsystems prior to a catastrophic event [37]. Additionally, traditional monitoring and control functions of IVHM systems are performed on an independent subsystem basis with relatively simple control laws. Thus, they are not considered essential to any safety critical function on-board [38]. A paradigm shift is required in the design of IVHM systems to accommodate the intelligence needs for future aerospace vehicles, autonomous systems, adaptive systems, and intuitive and highly networked engineering design environments. The research challenges corresponding to future intelligent IVHM systems include finding suitable methods and techniques for:

- performing real-time health monitoring functions to support accurate diagnosis of subsystem faults and anomalies;
- providing vital subsystem health and performance information with sufficient time to make real-time decisions in response to detected failures; and
- addressing the complete integration and management of all vehicle functions and subsystems by considering their interactions and fault causal relationships.

Intelligent IVHM would not only reduce ground maintenance but also increase vehicle safety and reliability by applying model-predictive and early-detection methods to dynamically reconfigure any faulty or degraded vehicle subsystem.

A proposed solution is based on the fact that intelligent IVHM requires the same sensors and processing capabilities as the real-time avionics functions in aerospace vehicles to support diagnosis of subsystem problems. The large volume of data captured by these onboard sensors offer the opportunity to leverage AI/ML techniques for the development of models of perception for sensor performance so as to support prediction of sensor anomalies and faults prior to their onset as well as the development of models of component/sub-system/system performance and failure modes to support intelligent IVHM. In particular, AI/ML offers promising opportunities to model highly nonlinear dependencies between raw sensor data and system performance [39]. Therefore, an opportune exploitation of data that is largely already being collected by on-board sensors in aerospace platforms can support the development of diagnostic and prognostic techniques to detect and reconfigure faulty vehicle subsystems prior to a catastrophic event.

CONCLUSION

As current, large-scale research and development initiatives are reshaping the future of aviation and space operations, avionics systems are becoming cyber-physical and progressively evolving into a variety of autonomous, intelligent, and closed-loop human–machine systems. This article provided the IEEE Aerospace & Electronic Systems Society (AESS) Avionics Systems Panel (ASP) views on avionics systems evolutionary pathways, with an identification of key research challenges and industry-focused innovation opportunities. The ever-increasing density of air traffic and the rise of unmanned aircraft systems (UAS) are prompting a rapid evolution of communication, navigation, surveillance/air traffic management (CNS/ATM) and avionics (CNS+A) technologies that will provide unprecedented enhancements in terms of safety and efficiency, thus unleashing additional airspace and airport capacity. Several of the underlying CNS technologies have already hit the market, while other more advanced capabilities and decision support systems are still being researched and developed. The methodological transition to performance-based operations (PBO) is also a quantum shift that will have profound impacts on aviation equipment mandates and standards with very tangible benefits in terms of airspace capacity, safety, access modalities, prioritization, and overall fairness. The PBO transition is well underway for navigation equipment standards and operational arrival/departure procedures, whereas communication and surveillance equipment is still currently following legacy mandates/equipage schemes. So, the full PBO paradigm evolutions require new harmonized CNS performance metrics and associated system-level hardware and software certification methods for integrated CNS+A systems. Another key challenge is in the evolutions of systems engineering and lifecycle management practices to encompass cyber-physical security and interoperability requirements. These transformations elicit the introduction of a viable certification scheme for ground-based ATM equipment and decision support systems (increasingly connected and integrated with their airborne counterparts) and to identify a viable approach to the safety certification of artificial intelligence (AI)/machine learning (ML) algorithms, which are becoming an essential technology in the CNS+A context. The conventional ATM network and services will be expanded to include new UAS and Space Traffic Management (UTM/STM) schemes for unsegregated operations of manned and autonomous vehicles both in atmospheric flight (including low-level and urban operations) and in near-Earth space operations. Finally, CNS+A technologies of the future will require advances in the design of human–machine interfaces and interactions (HMI^2) supporting trusted autonomous operations (human-autonomy teaming) and the full exploitation of intelligent health management technologies for a safe and automated system reconfiguration in presence of predicted or early-detected faults. Members of the AESS ASP are actively engaged in academia, Government, and industry to bring about technologies and innovation for a safer, secure, and efficient aviation. Readers are encouraged to contact the ASP for collaboration opportunities and exchange of ideas.

LIST OF ACRONYMS

4DT	Four-dimensional trajectory
ABAS	Aircraft-based augmentation system
ACP	Autonomous cyber-physical
ADS-B	Automatic dependent surveillance broadcast
AESS	Aerospace and Electronic Systems Society
AI	Artificial intelligence
ANSP	Air navigation service provider
AOC	Airline operation centers
APNT	Alternative position navigation and timing
AR	Augmented reality
ASBU	Aviation system block upgrade
ASM	Airspace management
ASP	Avionics systems panel
ATFCM	Air traffic flow and capacity management
ATFM	Air traffic flow management
ATM	Air traffic management
ATS	Air traffic services
ATSO	Air traffic service organization
BBB	Basic building blocks
BLOS	Beyond-line-of-sight
BVLOS	Beyond visual line-of-sight
C2	Command and control
CARATS	Collaborative action for renovation of air traffic systems
CDM	Collaborative decision making
CNS	Communication, navigation, and surveillance
CNS/ATM	Communication, navigation, and surveillance for air traffic management
CNS+A	CNS/ATM and avionics
CPH	Cyber-physical-human
CPS	Cyber-physical systems
DAM	Dynamic airspace management
DASC	Digital avionics systems conference
DDT&E	Design, development, test, and evaluation
DSS	Decision support system
EASA	European Union Aviation Safety Agency
FAA	Federal Aviation Administration
GANP	Global air navigation plan
GBAS	Ground based augmentation system
GNC	Guidance, navigation, and control

GNSS	Global navigation satellite systems
HMI^2	Human–machine interfaces and interactions
i4DT	Initial four-dimensional trajectory
IBO	Intent based operations
ICAO	International Civil Aviation Organization
ICNS	Integrated communications, navigation, and surveillance
iCPS	Intelligent cyber-physical systems
IoT	Internet of Things
IVHM	Integrated vehicle health management
MDA	Multidomain avionics
ML	Machine learning
MLAT	Multilateration
NASA	National Aeronautics and Space Administration
NextGen	Next Generation Air Transportation System
NG-ADL	Next generation aeronautical data link
NG-ATM	Next generation air traffic management
NG-FMS	Next generation flight management systems
OTM	One-to-many
PBC	Performance-based communication
PBN	Performance-based navigation
PBO	Performance-based operations
PBS	Performance-based surveillance
R&I	Research and innovation
SAA	Sense-and-avoid
S-ACP	Semiautonomous cyber-physical
SBAS	Space-based augmentation system
SESAR	Single European Sky ATM Research
STM	Space traffic management
sUAS	Small UAS
SWaP-C	Size, weight, power, and cost
SWIM	System wide information management
TAS	Trusted autonomous systems
TBO	Trajectory-based operations
TMA	Terminal maneuvering area
UAM	Urban air mobility
UAS	Unmanned aircraft system
UTM	UAS traffic management
VLOS	Visual line-of-sight
XAI	Explainable artificial intelligence

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