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# Next-Gen Embedded Systems in Aviation: Enhancing In-Flight Experience and Operations

**Arjun Agaram Mangad**

San Jose

aagarammangad@gmail.com

**Abstract**

**Aircrafts increasingly rely on embedded systems to enhance safety, efficiency, and passenger experience. This paper reviews existing applications of embedded systems in aviation, ranging from advanced avionics to in-flight entertainment (IFE) systems. It proposes new use cases that could shape the future of air travel. Current deployments such as fly-by-wire controls, predictive maintenance sensors, and seatback IFE networks are examined, highlighting their architecture and benefits. Building on this foundation, the paper introduces several novel concepts: an Internet of Things (IoT)-enabled smart cabin with sensor-integrated seats, real-time biometric-based passenger monitoring, and onboard AI-driven operational support. Each proposal is analyzed for technical feasibility, potential benefits, and challenges, including regulatory compliance, safety certification, cybersecurity, and integration complexities.The discussion underscores that while smart embedded systems promise significant improvements in airline operations and passenger comfort, careful design and compliance with aviation standards (e.g., physical network isolation for safety-critical systems) are necessary.**

**Keywords: Avionics, In-Flight Entertainment, IoT, Smart Cabin, Predictive Maintenance, Embedded Systems, Biometric Monitoring, Aircraft Connectivity.**

## I. Introduction

Embedded systems have long been at the heart of aviation technology, from digital flight controls to passenger entertainment units. A typical commercial airliner contained hundreds of microprocessors and complex software controlling flight, engine, and cabin functions. In modern jetliners, critical systems like flight control, navigation, and engine management are implemented via embedded computers in an integrated architecture known as avionics.

For instance, fly-by-wire control systems electronically manage aircraft stability and control surfaces, replacing mechanical linkages with software-defined responses for improved precision and safety. Similarly, full authority digital engine control (FADEC) units optimize engine performance in real time. These aviation-embedded systems must meet strict regulatory standards (RTCA DO-178C, DO-254) to ensure reliability under all conditions.

In parallel, the passenger-facing side of air travel has seen rapid adoption of embedded systems in the form of in-flight entertainment and connectivity (IFEC). Seatback IFE screens, cabin Wi-Fi, and smart cabin management systems have become common, enhancing the traveler experience on long flights. By the end of 2018, about one-third of commercial flights offered in-flight internet connectivity, and 25% of global passenger journeys (over 1 billion trips) took place on aircraft with onboard connectivity. This convergence of smart embedded systems in operational avionics and cabin services represents the dawn of the connected aircraft era.Despite significant progress, numerous opportunities remain to leverage embedded intelligence for further improvements.

This paper surveys aviation's state-of-the-art smart embedded systems, including avionics and IFE applications. It also proposes new concepts – from IoT-enabled cabins to AI-based assistance – that could feasibly be implemented with emerging technology. Each proposal has a technical workflow and is examined for benefits versus challenges such as safety certification, cybersecurity, and cost. The paper maintains a technical focus, aiming to inform both industry practitioners and researchers about the potential and pitfalls of next-generation embedded aviation systems.

## II. Existing Applications of Smart Embedded Systems in Aviation

### 1. Avionics and Flight Operations

Commercial aircraft have been evolving into complex cyber-physical systems with extensive embedded computing. Flight-critical functions are managed by networked avionics computers that must operate with high integrity. A prime example is the Integrated Modular Avionics (IMA) architecture used in Airbus A380, Boeing 787, and other latest-generation jets [1]. IMA consolidates multiple functions (flight controls, navigation, engine monitoring, etc.) onto common computing platforms with robust partitioning. High-speed data buses (e.g., ARINC 664/AFDX Ethernet) link these systems. For safety, avionics networks are strictly isolated from passenger networks,often by physical air gaps and firewalls which in-turn ensure that in-flight entertainment or Wi-Fi systems cannot interfere with navigation or control systems.

The reliability of these embedded platforms is evidenced by features like automatic redundancy and fault-tolerant control laws that allow aircraft to remain controllable even after multiple system failures.

Another key area is Aircraft Health Monitoring. Airliners carry extensive sensor suites on engines and airframe structures that feed data to onboard health management systems. For instance, vibration sensors and temperature probes continuously report engine performance to an Aircraft Condition Monitoring System (ACMS) [2]. Historically, maintenance data would be downloaded after landing; however, by 2018, new systems could transmit data via satellite or ground links in-flight, enabling real-time diagnostics [3]. Airlines began adopting predictive maintenance analytics to detect anomalies before they cause in-service failures. This proactive approach reduces aircraft downtime, improves safety, and cuts maintenance costs.

### 2. In-Flight Entertainment and Connectivity (IFEC)

In-flight entertainment systems are one of the most visible embedded technologies in the cabin. Early IFE systems consisted of shared overhead screens or projectors. By the 2000s, most long-haul aircraft featured seatbackentertainment units which are nothing but personal screens embedded in each seat, driven by content servers and distribution networks on the aircraft. A typical contemporary IFE network includes a head-end media server storing movies, TV, and music connected via wired networks (Ethernet or fiber optic) to seat electronic boxes and seatback displays throughout the cabin. These systems are essentially embedded computing networks – often running specialized operating systems. Many IFE systems also offer features like on-demand high-definition video, interactive 3D maps, games, and even in-seat ordering of food or duty-free items.

In-flight connectivity has become a major trend in the integration of IFE. Airlines have equipped aircraft with satellite communication antennas or air-to-ground transceivers to provide passengers with Wi-Fi internet access. This turns the aircraft into a flying hotspot, with an embedded network router linking to an external broadband pipe. The bandwidth available for air-to-ground systems in the U.S. could offer up to 100 Mbps per aircraft using 4G-based technology, while new high-throughput satellites (Ka-band) enable faster global Wi-Fi coverage [4].

3. Cabin Management and Other Smart Systems

Beyond entertainment, the passenger cabin hosts other embedded subsystems collectively managed by a Cabin Management System (CMS) [5]. The CMS controls overhead lighting, seat actuators, climate (air conditioning zones), galley equipment, passenger call buttons, and more. Many of these functions were historically isolated – e.g., a thermostat for each zone and separate switch panels for lights. Newer aircraft cabins integrate these into touch-screen interfaces for the crew (Flight Attendant Panels) and network the components for central monitoring.

## III. NEW PROPOSALS FOR SMART EMBEDDED SYSTEMS IN AVIATION ANDIFE

Building on the trends observed, this section proposes several forward-looking applications of smart embedded systems in aviation. Each proposal is chosen to be technically feasible with near-future technology and addresses real needs in airline operations or passenger experience. For each concept, a high-level workflow is described, followed by an analysis of potential benefits and challenges to implementation. The proposals include (a) an IoT-enabled smart cabin for enhanced operational awareness and passenger comfort, (b) real-time biometric-based passenger monitoring for security and health management, and (c) intelligent onboard systems for flight operations and maintenance. These concepts are not purely theoretical; many are extensions of prototypes or trials already in progress extrapolated to broader adoption. By examining these use cases, we aim to understand how emerging technologies like ubiquitous sensors, machine learning, and high-bandwidth connectivity could safely integrate into the aviation ecosystem.

1. IoT-Enabled "Smart Cabin" Infrastructure

The passenger cabin is one of the most promising areas for new embedded solutions, as seen with early connected cabin efforts (e.g., Airbus Connected Experience, there is considerable value in equipping the cabin with intelligence that can sense and react to conditions in real-time. The proposed fully IoT-enabled smart cabin system that networks many smart devices: seats, overhead bins, lavatories, gallery equipment, and environmental sensors (temperature, air quality, noise). The architecture would consist of wireless sensor nodes distributed throughout the cabin, communicating to central cabin hubs that interface with the aircraft's cabin management system and a cabin cloud server (for data analytics). Each passenger seat, for instance, would have embedded sensors for occupancy, seatbelt latch status, seat recline angle, tray table position, and even seat pocket contents. Overhead bins could have weight sensors or break-wire sensors to report if they are full or adequately latched. Lavatories might include occupancy sensors and consumable status (soap, water levels). The ovens and food carts can report inventory and equipment health.

Each smart device (seat, bin, etc.) sends status data to a Cabin IoT Gateway (wireless or via existing power line or data bus), aggregating the data. The Cabin Gateway forwards consolidated cabin status to the Central Cabin Management Controller (an embedded computer, possibly an enhanced CMS). Crew can monitor this via a tablet or the existing flight attendant panel, getting a real-time overview of cabin readiness (e.g., all seats upright, all bins closed) and passenger needs. The data is stored and uplinked to an Airline Cloud platform in real-time (if connectivity allows) or after landing, where further analytics (e.g., predictive cleaning/maintenance needs, usage statistics) can be performed. Crucially, the cabin IoT network is isolated from avionics for security, using a separate wireless spectrum or partitioned wired links.

This proposed smart cabin system would markedly improve situational awareness for crew and airline operations. Before takeoff, flight attendants could see briefly on a screen whose seats are not yet upright or whose seatbelts are unfastened rather than manually checking each row. They could be alerted if a life vest is missing from a seat (a common issue that is hard to detect manually). During the flight, if a passenger calls for service or looks for overhead space, the system could pinpoint the nearest open bin or notify if a lavatory is free. Upon landing, quick reports could indicate if any seat belts were left unbuckled or personal items left behind (via seat pocket sensors that detect forgotten items). The data collected for the airline's ops teams can feed into more efficient turnarounds – e.g., ground staff know which specific seat rows had service events, or which lavatories were heavily used and may need extra cleaning.

- Feasibility:

Many components needed to enable such a smart cabin are already available. Low-power wireless sensors (using protocols like Bluetooth Low Energy or ultra-wideband UWB) can operate for long durations on small batteries or even harvest energy, eliminating wiring. The bandwidth needed for seat and bin sensors is minimal so that a cabin network could piggyback on existing connectivity.

- Challenges:

The primary challenges are certification, data management, and security. Any wireless device on an aircraft must be proven not to interfere with avionics. Regulators would scrutinize adding hundreds of wireless sensors – rigorous testing under DO-160 (environmental/electromagnetic) standards would be required [6]. Cybersecurity is also a significant concern: although the cabin network is separate from flight systems, it could be a target for hackers if it connects to an onboard router or external link. Strong encryption and a firewall gateway would be necessary, and perhaps a design where the network can be physically shut off during critical flight phases to guarantee no interference. Data overload is another consideration – an aircraft could generate gigabytes of cabin sensor data per flight. Deciding what data to transmit live (perhaps only critical alerts) versus storing for later use will be important to manage bandwidth and cost. Airlines will also need back-end systems to analyze this data deluge (big data analytics platforms). Retrofitting older aircraft with smart cabin capabilities could be costly; embedding sensors into seats and bins is most straightforward on new production lines. However, as noted by manufacturers, a thoughtfully designed system can be modular and added during retrofit with minimal downtime. Despite these challenges, the smart cabin concept has clear momentum. Airlines stand to gain operational efficiencies (faster boarding checks, reduced missing item incidents, optimized maintenance of cabin equipment), and passengers benefit from a smoother, more personalized experience.

A likely implementation strategy is gradual: adopt smart galley carts for inventory tracking, add smart seats in premium cabins, and eventually scale to entire aircraft. Each incremental feature can be evaluated for ROI. Regulators like EASA and FAA have been approving limited wireless systems (e.g., Bluetooth headphone support, certain sensor trials), indicating the barriers are surmountable. The smart cabin is an excellent application of IoT in a constrained, safety-conscious environment, and it exemplifies the evolution of the airplane cabin into an information-rich, responsive space.

2. Real-Time Biometric-Based Passenger Monitoring for Security and Health Management

One of the emerging applications for smart embedded systems in aviationis biometric-based passenger monitoring. Airlines and airports have already been deploying facial recognition and fingerprint-based boarding to streamline passenger flow and enhance security [7], but in-flight biometric monitoring presents additional opportunities. Airlines could monitor passenger well-being in real-time using compact, unobtrusive embedded sensors. Sensors integrated into seat armrests or headrests could track heart rate variability, oxygen levels, and even signs of medical distress such as irregular breathing or sudden temperature drops. A biometric-enabled seat could automatically adjust recline and lumbar support based on detected muscle tension and posture, enhancing passenger comfort on long-haul flights. The workflow for such a system is described below: -

1. Embedded biometric sensors in seats, overhead bins, and lavatories collect real-time health and activity data.
2. This data is processed locally via an onboard IoT gateway to detect potential medical emergencies or anomalies.
3. If a serious issue is detected (e.g., a passenger showing signs of a stroke or cardiac arrest), an alert is sent to flight attendants' smart devices.
4. The onboard system prioritizes real-time alerts while logging non-critical data for post-flight analytics.
5. Upon landing, biometric reports can be shared with ground medical teams if a passenger requires immediate attention.

- Feasibility:

Biometric wearables such as smartwatches have already demonstrated the ability to detect early warning signs of medical conditions like atrial fibrillation. Integrating similar sensor technology into aircraft seats is technically viable, as low-power sensors can collect biometric data passively without requiring passenger intervention. Airlines could begin implementing biometric monitoring in premium cabins as an added-value feature before scaling it fleet-wide.

- Challenges:

As any new technology, there are a few challenges ( as noted below ) that must be overcome to succesfuly integrate this into aviation.

- Privacy and Data Security: Passengers must be assured that biometric data is used solely for health and security purposes and is not stored beyond the flight duration.
- Regulatory Compliance: Adhering to aviation and health data privacy laws (e.g., GDPR, HIPAA) is crucial for airline compliance.
- False Positives: Biometric alerts must be reliable enough to justify crew intervention without causing unnecessary panic.
- Technical Integration: Sensor data must be processed efficiently while maintaining cabin network security and compliance with aviation standards.

If implemented effectively, this system could provide significant benefits in medical emergencies, improve passenger comfort through smart seat adjustments, and enhance flight crew awareness of onboard health situations. As airlines increasingly focus on passenger well-being, biometric-based monitoring represents a novel yet technically feasible advancement in aviation-embedded systems.

3. Smart Embedded Systems for Flight Operations and Maintenance

The third proposal focuses on aircraft operations using embedded intelligence to support pilots and maintainers in real-time. While fully autonomous airliners remain a distant goal due to regulatory and public acceptance issues, there are intermediary steps where smart embedded systems could take on decision-support and automation tasks to improve safety and efficiency. An AI-based cockpit assistant system and an onboard predictive maintenance expert system are proposed as part of this section. Both would run on advanced airborne computer platforms (integrated into avionics or as separate systems) and provide recommendations or actions, but always with a human in the loop for final decisions.

- AI Cockpit Assistant:

Modern commercial jets already have auto-flight systems (autopilot, auto thrust) that can handle the bulk of flying under normal conditions. However, pilots still manage abnormal situations, complex decision-making (like rerouting for weather), and communications. An AI assistant could continuously monitor aircraft state, flight plans, weather, and ATC messages and offer suggestions or warnings. For example, it might use machine learning on past flight data to predict that a developing storm ahead will cause significant turbulence and recommend an optimal altitude or course change earlier than the flight crew might otherwise react. It could also cross-check for pilot actions, potentially catching human errors (acting like an advanced guardian system). In implementation, this might be an application running on an avionics computer or an attached processing unit, using sensor inputs and data link feeds. Its outputs would be via a cockpit display or a voice interface). This concept edges towards single-pilot operation by offloading tasks, but we consider it a virtual third crew member here.

- Onboard Predictive Maintenance Expert:

Complementing the above, an embedded maintenance AI on the aircraft can analyze sensor data in flight to predict failures more accurately than current threshold-based alerts. While health monitoring systems exist, an AI could use complex models (trained on big data from the fleet) to detect subtle anomalies. If it finds, for instance, that a fuel pump's vibration signature is deviating in a pattern that historically preceded a failure, it could notify pilots with a recommended action (e.g., "Pump 2 showing signs of wear, consider using Pump 1 primarily and schedule service"). This goes beyond the more straightforward ACMS alerts by using pattern recognition and perhaps reasoning – essentially bringing some capabilities of ground-based analytic platforms on board for immediate insights when connectivity is limited or in critical flight phases where quick decisions are needed (like diverting due to a technical issue).

- Feasibility:

The building blocks for such systems are already emerging: the increased processing power of aviation-grade hardware (for instance, advanced multi-core mission computers) and the development of robust algorithms. Moreover, quick access to vast data (via connectivity or ample onboard storage) makes training AI for specific airplanes feasible. A practical approach could be incremental – for example, implementing an AI focusing only on fuel management optimization or diagnosing engine start anomalies. The predictive maintenance AI on board could be an extension of the ACMS with added machine learning models; since many new aircraft (787, A350) already have maintenance operation calculators, adding AI software is plausible.

- Challenges:

The foremost challenge here is certification and trust. Any AI making recommendations that affect flight safety must be highly reliable and transparent. It is unacceptable to have a "black box" machine learning model influencing pilot decisions without pilots understanding the basis. Regulators would require deterministic behavior or at least proven safety benefits. One way around this is to keep AI assistants advisory only – not allowing them to control anything to present info directly. This still leaves the issue of potential information overload or pilot confusion if the AI is wrong. Human factors research would be needed to integrate this gently: pilots must feel it is an aid, not a nuisance or a threat to authority. There is also the matter of training the AI with enough diverse scenarios – rare emergencies are complex to learn from because data is scarce.

Another issue is integrating legacy systems: Avionics are tightly integrated and certified. Inserting an AI platform might require a separate computing environment that taps into sensors non-intrusively. This way, the AI system can be updated or improved without touching the certified core avionics. However, it also means any advice it gives is unofficial, complicating its use in operations.

- Benefits:

These intelligent embedded systems could significantly enhance safety and efficiency. The AI assistant might help catch errors (acting like a safety net for pilot situational awareness) and optimize flight decisions (saving fuel by suggesting better routes or speeds in real-time). The maintenance expert could prevent inflight diversions by advising action before a minor issue becomes major and ensuring that the airline is prepared at the destination with the right parts if something is degrading. Economic terms, even a tiny reduction in diversions or delays can save airlines millions.

Given the cautious nature of aviation, these systems would first appear as opt-in tools. For example, an airline might equip its fleet with a "smart dispatch aide" that rides along and is consulted by pilots for second opinions. As confidence and proven records build up (after extensive testing and refinement), such AIs could become standard. They will be a steppingstone to reduced crew operation and fully autonomous capabilities in decades. However, in the scope of our proposal, we envision them as embedded helpers that work within the current two-crew paradigm and maintenance processes, not replacing humans but augmenting them.

## IV. CHALLENGES AND CONSIDERATIONS

Across the proposed implementations, several common challenges must be addressed to move from concept to reality:

1. Certification and Safety Assurance:

Aviation is a high-stakes domain with catastrophic failures. Any new embedded system must undergo rigorous certification, especially those involving wireless communications (smart cabin) or AI decision-making (cockpit assistant). Industry standards (DO-178C for software, DO-254 for hardware) must be adapted to allow machine-learned components or novel architectures. Engaging regulators early, running extensive simulations and flight tests, and possibly restricting new tech to non-critical roles can help mitigate this hurdle.

2. Cybersecurity:

Greater connectivity comes with a greater risk of cyber-attacks. A smart cabin IoT network or an interactive IFE system could be entry points for attackers if not properly secured. The infamous scenario of hackers accessing flight controls via IFE was a topic of much debate in the late 2010s, although actual designs keep them isolated. It is essential to implement strong encryption, authentication, and continuous monitoring of all new embedded networks on the aircraft. This includes collaboration with standards bodies to update aviation cybersecurity guidance for IoT devices.

3. Data Management and Bandwidth:

The proposals generate and rely on large amounts of data. For instance, a single flight with a fully smart cabin could produce thousands of sensor readings per second. Handling this data onboard (storage, real-time processing) and offloading applicable portions to the ground will require robust data pipelines. Bandwidth to satellites is still expensive and limited, so deciding what data is critical (e.g., immediate maintenance alerts) versus what can wait until landing (e.g., detailed usage logs) is key. Airlines will also need back-end IT infrastructure (cloud databases, analytics) to store and utilize this data flood. Investing in data compression and edge processing (filtering data at source) will be beneficial.

4. Interoperability andStandardization:

Standards should be developed for industry-wide adoption so that sensors from different suppliers or aircraft models can communicate in a unified way. Efforts like ARINC specifications for cabin electronics or AID interfaces for data sharing must evolve to cover IoT frameworks. IFE, having common platforms would make it easier for different airlines to adopt without development for each airline.

5. Passenger Acceptance and Crew Training:

Introducing new tech affects people. Passengers may have privacy concerns with smart cabins (are the sensors monitoring them in uncomfortable ways?). Clear communication about what is and is not being recorded is important – e.g., seat sensors detect posture but do not record video or sound.It will likely remain an opt-in luxury at first. Crew and maintenance personnel will need training to work with these systems: cabin crew using tablets to manage the cabin or mechanics relying on AI recommendations – these change workflows and require updated training and trust-building through experience.

6. Cost-Benefit Tradeoffs:

Airlines operate on thin margins; any new system must justify its costs. Smart seats and wireless sensors add hardware and maintenance costs (battery replacements, etc.), so the benefits (faster turnaround, less staff workload, etc.) must be quantified. In safety/operations, the benefits might be avoidanceof rare but expensive events (like preventing one diversion could pay for the system). Careful analysis and possibly phased rollouts (pilot programs on a subset of the fleet) can help demonstrate the ROI to airlines' management.

## V. CONCLUSION

Smart embedded systems in aviation have already proven their value in both the cockpit and cabin, but the next generation of these technologies introduces fundamentally new capabilities that could redefine air travel. This paper explored how aircraft systems have evolved to incorporate networked embedded computers for flight control, predictive health monitoring, and in-flight entertainment while adhering to stringent aviation safety standards. Building on that foundation, we introduced forward-looking innovations—an IoT-enabled smart cabin, biometric-based passenger monitoring, and AI-driven operational assistance—that extend beyond incremental improvements to offer new paradigms in passenger experience, operational efficiency, and aviation safety.

The novelty of these concepts lies in their ability to create a more intelligent and responsive aviation ecosystem. A smart cabin transforms the aircraft interior into a dynamically monitored and well optimized environment, improving operational efficiency while enhancing passenger experience. Biometric-based passenger monitoring shifts in-flight health management from reactive to proactive, offering real-time well-being tracking that could revolutionize medical responses during flights. Meanwhile, AI-powered operational assistance introduces new layers of decision support for pilots and maintenance teams, leveraging machine learning to preemptively address system failures, optimize fuel usage, and enhance flight safety.

Adoption of these technologies will be influenced by both economic and regulatory factors. The cost-benefit equation will likely drive early implementation in premium market segments, where airlines can differentiate through enhanced services while proving the viability of these innovations. Over time, as regulatory frameworks evolve and integration costs decrease, these systems could become industry standards across commercial aviation.

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