System Architecture Design for Single Pilot Operations

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***Abstract*—The global aviation industry is struggling with a growing pilot shortage and rising operational costs. For this reason, Single Pilot Operations (SPO) has become one of the most important directions for the future of commercial aviation. This paper focuses on an SPO system architecture that ensures high safety, reliability, and flight efficiency. After analyzing key requirements including air-ground coordination, human-machine task distribution, and full-process flight automation, this paper proposes a four-party collaborative framework that includes the single pilot, an onboard intelligent core system, distributed ground support stations, and a cloud AI decision-making system. This paper also provides detailed designs for the intelligent decision-making module and the distributed ground support system, and evaluates its advantages in safety, efficiency, and scalability. Results show that this architecture can significantly reduce pilot workload, support better global flight decisions, and offer a practical technical plan for real-world SPO applications. At the same time, this study identifies technical and regulatory challenges that may slow down SPO implementation and offers possible solutions.**

***Keywords*—Single pilot operations, System architecture, Air-ground collaboration, Human-machine allocation, AI auxiliary decision-making**

I. INTRODUCTION

Since the 1950s, the number of crew members in commercial aircraft cockpits has decreased steadily from five to two. Today, Two-Crew Operations (TCO) represent the international standard. However, as global air traffic continues to expand, many airlines face a serious shortage of qualified pilots. Training and retaining pilots also add significant financial pressure on carriers [1]. Under these circumstances, Single Pilot Operations (SPO) has drawn wide attention from both industry and researchers, as it may solve labor shortages and improve overall operational efficiency [2].

Early SPO research led by NASA established a basic structure involving one onboard pilot, ground operators, and automated systems onboard and on the ground [2]. Most current studies focus on human-machine function allocation and automation technology, but few have built a complete, integrated architecture that connects aircraft, ground stations, and cloud systems. In addition, existing work often lacks detailed discussion of real-time air-ground cooperation and predictive support systems [3]. Technical implementation steps and regulatory compliance strategies also remain underexplored.

This study employs demand analysis, structural modeling, and module design to develop a practical SPO system architecture. Following safety-first principles and human-machine collaboration ideas, this paper discusses a four-party cooperative system and analyzes its performance, advantages, and implementation challenges. This paper can serve as a technical reference for airlines and manufacturers developing SPO systems.

II. SPO SYSTEM REQUIREMENT ANALYSIS

A. Air-ground Collaborative Operation and Remote Support

Moving from TCO to SPO changes how tasks are distributed. The traditional model of two pilots and machines becomes a triangular system involving one pilot, intelligent equipment, and remote ground support. The pilot handles high-level decisions and abnormal situations, while the ground side monitors flight conditions, provides expert advice, and can intervene remotely when needed. To support this model, the SPO system requires a stable, low-delay air-ground data link. Information must be transmitted accurately and in real time, and ground support resources must be allocated dynamically based on flight conditions [4].

B. Human-machine Function Allocation

The allocation of tasks between humans and machines is crucial for ensuring the safety and efficacy of Single Pilot Operations (SPO). In comparison to traditional Crew Resource Management (TCO), SPO must reassign flight duties among the pilot, onboard automation, ground staff, and ground-based automated systems. Routine operations such as route planning, guidance, and basic control should be managed automatically. The pilot should focus on monitoring flight status, identifying risks, and making critical emergency decisions. A reasonable allocation reduces workload without lowering the pilot's situational awareness. Over-automation must be avoided to prevent the pilot from becoming disconnected from the flight process [3].

C. Full-process Flight Automation and Auxiliary Decision-making

An effective SPO system must support automation across the entire flight, from pre-flight planning through to landing. It extends beyond basic automation by incorporating intelligent decision-making tools capable of analyzing real-time flight data, airspace restrictions, and weather conditions. The system needs intelligent decision-making tools that analyze real-time flight data, airspace restrictions, and weather forecasts. It should diagnose equipment problems, optimize routes, and avoid dangerous weather independently [3]. During emergencies, the system must quickly provide clear, step-by-step response suggestions to both the pilot and ground team, improving overall emergency response capability.

III. OVERALL ARCHITECTURE DESIGN OF SPO SYSTEM

A. Design Principles

Two main principles guided this design: safety priority and human-machine cooperation. Safety is embedded throughout the architecture through distributed structures, predictive warnings, and multi-level redundancy to prevent accidents caused by single-point failures. Human-machine cooperation ensures that the pilot retains authority and situational awareness while machines handle repetitive and precise tasks. Clear boundaries between human and machine responsibilities support stable and efficient teamwork [5].

B . Overall Architecture Model

This paper presents a four-party collaborative SPO architecture consisting of the single onboard pilot, the onboard intelligent central system, distributed ground support nodes, and a cloud AI auxiliary decision-making system. Together, these components form a closed-loop system for flight control, monitoring, and support covering the entire flight.

The onboard intelligent central system is the core of in-flight operations. It includes the flight management system, intelligent decision support, pilot status monitoring, and human-machine interfaces. It executes flight actions, monitors the pilot’s condition, and serves as the communication bridge between the aircraft, ground, and cloud [1].

Distributed ground support nodes include remote consoles, data centers, and ATC interface modules spread across different airspace regions. They monitor flights in real time, assist with decisions, and communicate with air traffic control. The distributed structure improves reliability by preventing total system failure due to one node breaking down [6].

The cloud AI system acts as a global decision engine, integrating real-time flight data, updates on airspace conditions, weather information, and historical data to deliver optimized suggestions for flight operations. Additionally, it enhances predictive operations by identifying potential risks such as route congestion or equipment issues early, allowing ground resources to be arranged proactively.

IV. DETAILED SYSTEM DESIGN

A . On-board Intelligent Auxiliary Decision-making System

The onboard intelligent decision-making system supports the pilot through four main functions: fault detection, route optimization, weather avoidance, and emergency recommendations. It uses a human-machine interaction model based on intelligent reminders, manual confirmation, and layered authority control.

The fault diagnosis module collects equipment data and tracks performance in real time. It can identify fault types and locations quickly and alert the pilot immediately. The route optimization module uses cloud-based airspace and weather data to adjust the flight path dynamically, reducing delays and improving efficiency. The weather avoidance module monitors storm movement and suggests safe detours. The emergency module uses a built-in response database to provide clear procedures for equipment failures, extreme weather, and other crises.

In terms of interaction, the system shows suggestions on cockpit displays but does not act without pilot confirmation. Authority levels separate pilot-controlled actions from automated functions, allowing flexible switching based on flight phase and safety needs [7].

B . Distributed Ground Support System

The distributed ground support system provides remote assistance in three ways: real-time monitoring, operational intervention, and decision support.

The monitoring module receives flight data such as altitude, speed, heading, and equipment status through the air-ground link. Ground staff can view visual flight dashboards and stay fully aware of conditions. The intervention module allows ground personnel to take over limited functions if authorized by the pilot or in extreme emergencies such as pilot incapacitation. The decision support module combines onboard and cloud data to give professional recommendations for route changes, fault handling, and emergency responses [3, 6].

Ground nodes communicate with the cloud and aircraft through dedicated communication networks, enabling instant information sharing. The cloud system dynamically assigns support tasks to the most suitable ground station based on the flight path and current situation, improving response efficiency.

V. ARCHITECTURE ADVANTAGES

A . High Safety

The proposed architecture improves safety in multiple ways. Firstly, distributed ground stations eliminate single points of failure, so the system remains functional even if one station fails. Secondly, the cloud AI system predicts risks before they become dangerous, supporting preventive actions. Thirdly, the onboard system adjusts operations based on pilot workload and status, reducing fatigue-related risks [8]. Additional redundancy in communication links and authority layers further strengthens safety.

B . High Efficiency

The four-party structure significantly enhances global flight and support operations, leveraging cloud-based data integration for improved route planning and efficient allocation of ground resources. This integration effectively reduces unnecessary flight durations and delays. Additionally, the automation of routine tasks allows pilots to concentrate on higher-level decision-making, which boosts overall task efficiency. Furthermore, the swift and direct sharing of information between aircraft, ground personnel, and cloud systems diminishes superfluous communication, thereby expediting decision-making processes.

C . Strong Scalability

The system uses a modular design, making it highly adaptable. Parameters can be adjusted for different aircraft types, and new modules can be added for special conditions such as long-haul overwater flights or high-altitude routes. Moreover, the open interfaces facilitate the future integration of improved AI models, advanced sensors, and better pilot monitoring tools. This inherent flexibility ensures that the system continues to evolve in tandem with advancements in aviation technology.

VI. IMPLEMENTATION CHALLENGES

This section discusses two primary categories of challenges regarding the deployment of Single Pilot

Operations (SPO) in aviation: technical and regulatory challenges.

A. Technical Challenges

The successful implementation of SPO necessitates overcoming significant technical hurdles, specifically in low-latency communication between the cloud and aircraft, as well as the use of lightweight AI models. Real-time data transmission between the cloud and aircraft is essential, but current communication systems often lack sufficient speed and bandwidth [9]. On top of that, advanced AI models are too large for onboard computing systems. They must be compressed and optimized without losing accuracy [10].

B. Regulatory Challenges

Regulatory challenges mainly involve ground support station certification and responsibility definition. Current aviation rules were created for traditional two-pilot operations. No unified standards exist for training, licensing, or managing ground support personnel and stations [11, 12]. New hierarchical certification rules must be developed with regulators. Liability is also unclear: responsibility in an emergency would involve the pilot, ground team, airline, and system developers. Without clear legal boundaries, blame disputes could arise after incidents.

VII. Conclusion

This paper focuses on Single Pilot Operations as a solution to pilot shortages and rising airline costs. By analyzing air-ground cooperation, human-machine allocation, and full-process automation needs, this paper discusses a four-party collaborative SPO architecture including the pilot, intelligent onboard system, distributed ground stations, and cloud AI decision support. Detailed designs for key subsystems are also provided.

The architecture offers strong safety, high efficiency, and good scalability. Distributed ground support and predictive cloud intelligence improve security. Global route and resource optimization increase efficiency. Modular design allows broad adaptability across aircraft and scenarios. This study also recognizes technical and regulatory challenges, including communication latency, AI lightweighting, station certification, and responsibility division, and proposes directions for solutions.

This research remains theoretical and has not been verified through physical or simulated testing. Future work should build a simulation platform to test key functions and optimize the structure accordingly. In addition, regulatory frameworks require deeper exploration to support safe and legal SPO deployment.

Future SPO research should advance in three areas: reliable low-latency communication using 5G, 6G, or satellite technology; lightweight and efficient AI models for onboard use; and refined human-machine collaboration strategies. As technology matures and regulations improve, SPO will likely become a practical and widely used model in commercial aviation.

Conflict of Interest

The author declares no conflict of interest.

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