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Technical Analysis of Ground-Based Remote Takeover of In-Flight Scenario Restoration

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Abstract:
This paper systematically analyses the development history of flight simulators and the current state of research into overload simulation accuracy, focusing on scene reproduction technology during ground-based remote takeover flights. The evolution from mechanical simulators to algorithm-driven and digitally integrated systems is reviewed, highlighting their critical role in Single-Pilot Operations (SPO). It further elaborates on significant advances in high-dynamic overload simulation technology concerning dynamic modelling, real-time motion planning, and multi-axis overload reproduction. Centrifuge-based simulation platforms have achieved breakthroughs in structural design, control systems, and integrated systems, enhancing the fidelity of ground-based simulation. However, research also indicates that current technology still faces challenges in multi-system coordination, the realism of low-G simulation, and human-machine adaptability. Future development, therefore, requires more intelligent motion control algorithms, enhanced human factors and ergonomics research, and the integration of digital twins with simulation systems. These advancements are essential to robustly support the ground simulation requirements for evolving ‘single-pilot operation’ and future autonomous flight modes.

Keywords: flight simulator; ground-based remote takeover; scenario reproduction technology; G-force simulation accuracy

1. Introduction

Over recent decades, technological advancements have driven significant transformations in the operational modes of large commercial aircraft. Cockpit crews have progressively reduced from five members to three (comprising one captain and two first officers), with this trend towards further reduction continuing. Consequently, avionics architectures supporting single-pilot operation (SPO) have emerged

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as a core development focus. Initial SPO research encompassed two primary design approaches [1-4]. One approach was the remote ground station support scheme. This 'air-ground centred' solution transferred part of the co-pilot's duties from the air to the ground [5]. The ground-based remote takeover technology within this scheme enabled ground operators to intervene and control the aircraft in real-time when necessary, significantly enhancing flight system safety and flexibility. Flight simulators, as vital ground-based simulation equipment, can replicate an aircraft's in-flight attitude and dynamic characteristics under laboratory conditions [6]. The ground flight simulator thus assumes critical importance for ground station operators, directly impacting flight safety. It plays a vital role during takeover operations, not only refining pilots' control techniques but also enhancing their decision-making and response capabilities during emergencies. Furthermore, it precisely replicates pilots' physiological and psychological states, enabling ground operators to experience near-realistic flight conditions within a virtual environment.

Modern full-mission flight simulators are undergoing a functional leap from 'training tools' to 'real-time control nodes'. However, due to factors such as sensor latency, modelling errors, and human-machine perceptual differences, the motion states, visual scenes, and haptic feedback presented in the virtual environment still exhibit perceptible systematic errors compared to actual flight. This directly impacts the judgement and operational effectiveness of ground operators. Systematically analysing and mitigating such discrepancies to enhance consistency between simulated and actual flight conditions constitutes the core research direction summarised and presented herein.

2. Development and Evolution of Flight Simulator Technology

2.1 Mechanical Simulation

Given that aircraft encounter diverse external environmental disturbances and airframe condition changes during flight, flight simulators must achieve genuine 'simulation' to enable ground operators to effectively take control when the pilot-in-command becomes incapacitated. The most influential and representative early example of this research was the Antoinette simulator [7]. To simulate the pilot's pitch and roll movements, the pilot's seat was mounted on two half-barrels, requiring an assistant to manually adjust the simulator's attitude while simultaneously manipulating the pilot to maintain balance. This demonstrates that early scientists already valued the scene reproduction technology of flight simulators, with such equipment laying the foundation for the further maturation of future flight simulators.

In 1930, Edwin Link invented the world's first flight simulator – the Link Trainer. However, constrained by the limitations of the time, this simulator could only perform simple piloting simulations and was unable to replicate the true dynamic sensations of an aircraft [8].

2.2 Algorithm-Driven Simulation

During flight, aircraft undergo diverse motion states. Their dynamic behaviour often exhibits high complexity due to external environmental factors and airflow disturbances. This complexity is directly reflected in the dynamic signals generated by the aircraft, which typically encompass broadband components spanning low to high frequencies. To faithfully reproduce such flight conditions, motion simulation algorithms (also termed washout algorithms) are extensively employed in flight simulators. Recent research in this field has focused on optimising algorithm performance through adaptive control and model prediction strategies to address challenges such as system latency and sensory distortion [9]. The algorithm calculates the required acceleration and Euler angle changes across each degree of freedom of the simulator's motion system. These values are then converted via inverse kinematics into drive commands for the hydraulic cylinders, ultimately enabling hydraulic actuators to deliver motion feedback approximating authentic flight experiences [10].

2.3 Digital Integrated Simulation

British engineer Stewart pioneered the six-degree-of-freedom parallel mechanism in 1965 [11], revolutionising traditional flight simulator concepts and significantly enhancing simulation accuracy. This marked a pivotal milestone in flight simulator development. Furthermore, by the 1980s, researchers had begun integrating centrifuges with aircraft flight simulators to enhance pilots' physiological perception under prolonged sustained acceleration. This approach more authentically reproduced the complex motion states encountered during high-altitude flight or aggressive manoeuvres. Such integrated solutions not only enhanced the simulator's dynamic response capabilities but also broadened its application scope across military training and civil aviation domains.

This research has garnered significant international attention. The United States has constructed multiple dynamic flight simulators since the last century, whereas China commenced its flight simulator research somewhat later. ETC (United States), Latecoere (France), and AMST

(Austria) currently represent the most advanced companies in high-dynamic flight simulator development. ETC's ATFS-400 system represents the pinnacle of current technological achievement. As illustrated in Figure 1, this simulator achieves a maximum start-up rate of 15G/s and delivers peak accelerations of 20G across three axes. Furthermore, it integrates closed-loop control systems, environmental control systems, and visual systems, enabling diverse flight training scenarios and complex physiological research. It also simulates an aircraft's aerodynamic performance and mission systems across multiple operational environments.

Fig. 1 ATFS-400 Dynamic Flight Simulator [10]

3. Current Research Status on Overload Simulation Accuracy Domesticallyand Internationally

Simulation fidelity is determined by the degree of matching between the simulator and the actual aircraft's flight conditions, environmental parameters, and motion responses [12]. Overload simulation accuracy is a key metric for evaluating flight simulation fidelity, directly reflecting the simulator's capability to reproduce theoretical overload commands. However, academic research into its driving factors remains limited, with existing work predominantly concentrated in specific domains.

3.1 System Response Delay

To date, no unified response performance standard has been proposed for dynamic flight simulators. The industry widely adopts the technical standards established by the Federal Aviation Administration (FAA) for actuator-based simulators as practical guidelines [13]. Recent research indicates that employing adaptive delay compensation and control frameworks can effectively analyse and compensate for system delays, significantly enhancing both the accuracy and real-time performance of overload simulation [14]. Enhancing electromechanical controller performance can reduce reaction times and improve overload simulation accuracy; however, balancing real-time capability with control precision warrants further investigation.

3.2 Mechanical Structure Optimisation

High-speed operation poses significant challenges to rotating components in dynamic flight simulators, which must withstand high dynamic loads from frequent acceleration and deceleration while achieving lightweight construction without compromising structural integrity. Yet, the goal of weight reduction conflicts with the requirement to suppress Coriolis acceleration: increasing the radius of motion reduces the Coriolis effect but leads to a substantial increase in structural mass and inertia, consequently raising the cost of the drive system [10]. Current research focuses on resolving this conflict through topology optimisation and the application of novel materials. For instance, employing carbon fibre reinforced polymer (CFRP) to manufacture key components of the motion simulator can significantly reduce inertia while ensuring sufficient stiffness. Furthermore, hybrid-link configurations have emerged as a trend, combining the high rigidity of parallel mechanisms with the extensive workspace of serial mechanisms to fundamentally enhance motion performance through mechanical design.

3.3 Motion Control Algorithms

Motion control algorithms serve as the core link between commands and actuators, with their performance directly determining the accuracy of overload simulation. Traditional PID control struggles to address complex issues such as system nonlinearity, coupling, and delays. Consequently, advanced control strategies have emerged as a

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research focus for enhancing overload simulation accuracy. Adaptive control and disturbance observers: These methodologies enable online estimation and compensation for system model uncertainties, external disturbances, and nonlinear factors such as friction. For instance, Li et al. proposed an adaptive sliding mode control strategy for parallel robots, effectively suppressing disturbances and improving trajectory tracking accuracy [15].

4. Flight Simulator Technology Updates

The rapid advancement of modern aviation technology has driven flight simulators towards 'single-pilot operation' (SPO) and 'ground remote takeover' modes, imposing heightened demands on their realism, responsiveness, and intelligence. Flight simulators have transcended their role as mere training tools, evolving into critical ground nodes integrating real-time control, status monitoring, and decision support. Key technological advancements manifest in the following areas.

4.1 Breakthroughs in High-Dynamic Overload Simulation Technology

In recent years, significant progress has been achieved in the dynamic modelling and motion control of high-overload flight simulators, with particular technological breakthroughs in high-precision overload simulation and real-time motion parameter planning. Research by Huang Yujin demonstrates that establishing a three-degree-of-freedom dynamic model based on the D-H method, combined with the Newton-Euler iterative algorithm, enables precise calculation of angular velocity and angular acceleration for each component, providing a robust theoretical foundation for high-dynamic overload simulation [10]. Addressing the challenge of real-time motion parameter planning during overload simulation—particularly the difficulties and substantial errors encountered with traditional methods during high-overload unloading phases—this research proposes a motion planning algorithm. This approach constructs a query database from loading-phase data and employs linear interpolation. By pre-computing motion parameters for various overload levels and rates of change, it enables rapid mapping and interpolation during unloading, ensuring computational efficiency while significantly enhancing simulation accuracy. Simulation results demonstrate that in unidirectional overload scenarios, thoracic-dorsal errors can be reduced to 10–16g, with cephalopodal errors not exceeding 0.1g. Under triaxial compound overload conditions, although errors fluctuate with overload rate of change, overall performance remains within acceptable limits. The root mean square deviation remains stable, meeting the specifications for high-overload training. Regarding engineering implementation, the research also completed the development of high-dynamic control software based on the Qt platform. This integrates real-time communication, status monitoring, and three-dimensional trajectory display functions, supporting multiple operational modes including manual, curve, closed-loop, and offline simulation. It provides systematic support for the practical application of the algorithms [10]. These technological achievements not only enhance the dynamic response and simulation accuracy of high-overload flight simulators but also provide a crucial technical foundation for their applicability in novel flight control modes such as 'ground remote takeover'. This facilitates the evolution of simulators from traditional training tools to functional real-time control nodes.

4.2 Key Technology Research for High-G Centrifugal Flight Simulation Platform Systems

High-G flight simulation platform systems represent a significant developmental direction in contemporary flight simulator technology, demonstrating notable technical advancements in structural design, motion control, and simulation fidelity. Centred around a centrifuge as the primary motion platform, this system generates sustained centrifugal overload through main arm rotation. Combined with dual-degree-of-freedom motion—roll via the central frame and pitch via the basket—it achieves precise simulation of multi-axis overload environments encountered during flight. Mechanically, the adoption of an eye-level horizontal rotation axis design effectively mitigates Coriolis acceleration interference affecting the vestibular system, enhancing pilot comfort and safety. The power and electrical systems employ an EtherCAT fieldbus to establish a high-real-time communication network. Integrated with the TwinCAT real-time kernel, this enables high-precision synchronous control of torque motors, ensuring stable system operation under high-speed, high-acceleration-rate conditions. The software system integrates functional modules including communication interaction, equipment monitoring, multi-mode control, trajectory animation, and safety protection. It supports diverse training modes ranging from offline simulation to closed-loop online operation, offering excellent scalability and human-machine interaction performance [16]. This platform not only simulates overload environments up to 20G but also supports dynamic response flight envelope data, achieving high fidelity reproduction of real flight scenarios. It provides a reliable ground-based simulation method for pilots to withstand high-G simulated driving, demonstrating strong engineering application value and military training significance.

5. Summary

This paper systematically analyses the evolution of flight simulators, the current state of research into overload simulation accuracy, and technological advancements under novel flight control modes, focusing on scenario reproduction techniques for ground-based remote takeover flight operations. Research indicates significant progress in high-G flight simulators concerning dynamic modelling, real-time motion planning, and multi-axis overload simulation. Technological breakthroughs have been achieved particularly in database-interpolation-based motion control algorithms, high-dynamic centrifuge platform integration, and real-time software system development.

Nevertheless, it must be acknowledged that current high-G simulation technology still faces several challenges. Tracking errors persist during rapid G-rate transitions, simulation fidelity remains limited in low-G ranges, and latency and synchronisation issues within multi-system cooperative control have yet to be fully resolved. Furthermore, existing research predominantly focuses on the motion simulation of the equipment itself, with insufficient attention given to assessing physiological perception consistency and human factors adaptation within the pilot-in-the-loop environment.

Future research may advance in the following directions: firstly, developing more efficient and adaptive motion control algorithms to enhance simulation accuracy and stability under complex dynamic overload scenarios; secondly, deepening human-machine ergonomics research to establish a combined objective-subjective fidelity evaluation system, with particular emphasis on ground pilot cognitive load and situational awareness during remote takeover procedures. This will provide robust ground simulation support for future single-pilot operations and fully autonomous flight.

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