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Status and Challenges of Digital Modeling for Typical Aircraft Control Objects

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Abstract. As a core segment of national high-end manufacturing, the aviation industry relies heavily on aircraft control components that directly determine flight safety and handling performance. Digital modeling has become a mainstream technical approach for developing aviation equipment. Taking typical control components such as steering gears and flight control actuators as research objects, this paper sorts out their multi-domain structural features and coupling mechanisms across mechanical, hydraulic and electrical fields, laying a theoretical foundation for modeling. To address the accuracy limitations of traditional single-domain modeling, this paper explores approaches to balancing model complexity and simulation fidelity, develops multi-system coupled digital models, and performs simulation tests. By comparing simulated outputs with actual operating condition data, this paper analyzes the causes of deviations between them. Finally, various technical bottlenecks existing in current digital modeling and simulation are summarized. The research results indicate that integrating digital twin architecture with model-driven design can effectively mitigate insufficient accuracy in single-domain modeling. Nevertheless, prominent technical obstacles remain in accurately depicting multi-physics dynamic coupling and establishing standardized model verification that covers full operating conditions. The conclusions of this research can provide clear ideas and references for optimizing multi-domain coupled modeling of aircraft and the digital development of flight control equipment.

Keywords: multi-system coupled modeling, aircraft control model, simulation analysis, model-driven design

1. Introduction

The aviation industry stands as a core field of national high-end manufacturing and defense technology. Modern aircraft are increasingly complex and integrated. As core executive components, typical control objects such as steering gears and flight control actuators feature multi-domain coupled operating characteristics that directly govern flight control precision and safety performance. Traditional development of aviation equipment depends on physical prototyping and experimental testing, which are plagued by high costs, long cycles and poor repeatability, failing to meet the demands of rapid iterative aircraft development nowadays. Driven by rapid advances in digital technologies such as digital twins and model-driven design, these approaches have gradually

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replaced conventional testing modes and become core tools for modeling, simulation and optimization of aviation equipment.

However, aircraft control objects involve multi-physics fields of machinery, hydraulics and electricity. Conventional single-domain modeling methods cannot accurately capture multi-system coupling effects, resulting in low model fidelity, poor trade-offs between simulation accuracy and efficiency, and an imperfect verification system. Domestic and foreign scholars have achieved certain research outcomes in digital twin modeling and model-driven optimal design for aviation components, yet most studies focus on aero-engines, fuselages and environmental control equipment. Systematic research on multi-domain coupled modeling dedicated to typical flight control objects is scarce, and there is a lack of mature modeling and simulation verification frameworks, which forms a major research gap in this field.

Against this backdrop, this paper adopts literature research, mechanism analysis and comparative simulation analysis. It focuses on the technical architecture and aviation applications of digital twin technology, as well as the theories and engineering implementations of model-driven design. The multi-domain coupled modeling methods for aircraft control objects are systematically investigated, and the technical shortcomings and core challenges of current digital modeling are identified and summarized. This research can enrich the theories of multi-system coupled modeling for flight control components, offer references for digital development and simulation system optimization of aviation flight control equipment, and facilitate the digital transformation of China's aviation industry.

2. Digital twin technology

2.1. Core characteristics and technical architecture of digital twin

Digital twin technology establishes virtual models synchronized with physical entities in real time via sensors, the Internet of Things (IoT) and other tools, supporting simulation analysis and decision optimization with a closed-loop capability of "perception – modeling – analysis – optimization – feedback". It integrates multiple technologies including modeling, simulation and data transmission [1, 2]. Its core characteristics are as follows: First, dynamic mapping. Real-time data streams enable state synchronization between virtual models and physical entities, with update delays precisely controlled at the millisecond level. Second, full lifecycle coverage. It covers the whole process of physical entities from design, manufacturing and operation to decommissioning, completely recording all types of lifecycle data. Third, multi-dimensional integration. It unifies geometric modeling, physical simulation, data analysis, artificial intelligence and other cross-disciplinary technologies to realize coupled analysis of multi-physics fields. Fourth, decision support. Scenario simulation and predictive analysis can provide a scientific and reliable basis for decision-making in engineering optimization, risk early warning and resource allocation.

The core architecture of a digital twin system involves five interrelated functional layers that jointly support virtual-physical integration and intelligent operational management. The Physical Entity Layer covers core physical hardware including aircraft fuselages and aero-engines, alongside sensor networks responsible for collecting real-time operational data such as temperature and pressure indicators. The Virtual Model Layer adopts multi-physics simulation technologies to construct high-fidelity models that integrate geometric, physical, behavioral, and rule-based characteristics, which enables multi-scenario simulation analysis and accurate equipment performance prediction. The Service Application Layer provides tailored functional services throughout the full equipment lifecycle, including predictive maintenance, structural design

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optimization, emission accounting, and intelligent route planning, so as to facilitate data-driven and scientific decision-making. The Communication Network Layer relies on 5G communication technology, edge computing, and Internet of Things infrastructure to deliver low-latency and highly reliable data transmission between physical entities and virtual models, ensuring efficient and real-time virtual-physical interaction. Serving as the fundamental data support of the entire system, the Data Fusion Layer aggregates multi-source information ranging from real-time sensor measurements and historical operation and maintenance records to professional design specifications and environmental monitoring data, and it constructs standardized and high-quality datasets after systematic data cleaning and deep fusion processing.

The digital twin technical architecture adopts a bottom-up structure with six functional layers. The physical layer acts as the fundamental data source, covering on-site personnel, equipment, and product entities. The data layer collects multi-source data via 5G and Internet of Things, connects enterprise business systems, and unifies data standards based on specifications such as the Bill of Materials. The model layer constructs full lifecycle high-fidelity virtual models throughout manufacturing and maintenance processes through geometric, physical, behavioral, and logical modeling. The function layer implements core twin capabilities for process planning, production, assembly, and maintenance, while the application layer integrates visual monitoring, predictive analysis, and other decision-support functions through enterprise-level twin platforms. These layers form a closed-loop iterative system that enables dynamic control and continuous optimization of the full aero-engine manufacturing lifecycle. The proposed architecture supports end-to-end management from process planning to quality verification and improves overall system efficiency and operational stability [3].

2.2. Typical application cases of digital twin technology

Rapid and continuous digital design iteration plays a vital role in the aerospace industry. SpaceX completed 134 orbital launch missions in 2024, a year-on-year increase of 39.6%, and these missions accounted for over 51.7% of the global total of 259 launches [2]. Digital twin technology is mainly applied to aircraft R&D, manufacturing, assembly and operation and maintenance. It can also be used for pre-launch flight test analysis, real-time monitoring of payloads and structural damage, post-fault or post-damage assessment, and for use as an analytical platform for design revision [4].

COMAC built a full-lifecycle digital twin system for the C919 passenger aircraft covering design, manufacturing, operation and retirement. During the design phase, multi-physics simulation optimized fuselage structures to reduce physical prototype trials. In manufacturing, production workflows were monitored in real time to control energy consumption and emissions. For operation, a virtual replica was created for each aircraft to track flight status and deliver predictive maintenance. At the decommissioning stage, disassembly and recycling strategies were optimized. Compared with traditional modes, this system significantly improved all lifecycle indicators of the C919.

Beijing Daxing International Airport constructed an integrated "Entity-Model-Middle Platform" system that incorporates 15 categories of data, including air traffic control, flight schedules and energy consumption. It realizes four core functions: dynamic optimization of flight routes and taxi paths, coordination of ground operations and baggage allocation, intelligent energy regulation of terminal buildings, and simulation of extreme weather scenarios to formulate emergency response plans. After deployment, the airport outperformed industry averages in flight punctuality rate, unit energy consumption, taxi time and emergency response efficiency.

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Cao et al. conducted research on digital twin models targeting complex multi-physics coupling problems during the manufacturing of core aero-engine components [5]. They established a multi-physics coupled digital twin model incorporating thermodynamics, fluid mechanics and structural mechanics. Simulation analysis of component performance and fault prediction were carried out to provide a basis for design optimization.

The research realized process simulation and virtual manufacturing via digital twins. By combining IoT and AI technologies,the research achieved real-time state mapping, data integration and intelligent prediction across the full lifecycle of aero-engines were achieved. The model can accurately simulate component conditions and effectively boost manufacturing efficiency and product qualification rates. However, current research remains at an initial stage of one-way data display and static rule design, lacking closed-loop optimization through two-way interaction and data-driven intelligent evolution. Future breakthroughs are required in precise multi-physics modeling, dynamic closed-loop control and autonomous decision-making to realize full-factor and full-process digital twin applications.

3. Model-driven design

Over the past seventy years, aero-engine control architecture has evolved from low-precision, purely mechanical systems in piston engines to advanced full-authority digital control systems in the late 20th century, which enable automatic tuning and self-diagnosis. The transition now aims for distributed intelligent control to optimize power output and emissions. The proposed ACPS architecture addresses limitations in flexible assembly simulation, focusing on system architecture, motion trajectories, and equipment coordination for large-component docking. Modern aero-engines demand high performance and environmental standards, leading to a focus on advanced algorithms like robust scheduling and model predictive control as key research areas.

3.1. Scheme design for aviation applications

Aviation products operate in harsh environments including high-speed airflow and extreme temperatures. Design schemes derived from conventional methods often fail to balance aerodynamic and structural demands [6]. This paper proposes a systematic closed-loop technical workflow for the design and innovation of key aviation components, built on general functional descriptions of key aviation components, with a dual-driven framework of theoretical support and knowledge mining.

First, system functional models are constructed for key aviation components to characterize structural coupling features. Next, functions and system components are identified according to functional-structure hierarchy rules. The correlation between structural components and system functions is further quantified to lay a theoretical foundation for subsequent design optimization.

Patent similarity analysis, which focuses on patent analysis and knowledge mining, is performed based on functions and structures. Major technical fields are identified from functional similarity results, and these core domains are mapped to cross-disciplinary spaces to search for alternative systems. Core patents are determined via structural component similarity, completing preliminary patent screening and extraction of alternative systems.

After theoretical modeling and knowledge extraction, the workflow enters the core analogical design stage. The system functional model of the original system is deeply matched with functional models extracted from alternative systems identified from patents, and structural components of alternative systems are extracted to realize innovative design through functional analogy. Improved schemes and conceptual design proposals for key aviation components are generated accordingly.

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On this basis, reverse optimization iteration is carried out to generate initial optimal schemes and iterative versions, which eventually converge into the final design proposal for key aviation components. The whole closed-loop workflow covers functional modeling, patent knowledge utilization, analogical innovation and iterative optimization, providing a systematic technical path for efficient innovative design of key aviation components.

Experiments adopt virtual programs as platforms with two types of pre-experiment videos [7]. The first type is project overview videos that comprehensively introduce the general experiment background, featured technical tools, application scenarios and future plans, mainly to stimulate students' interest in experimental learning. The second type is instructional guidance videos detailing experiment names, environments, content, requirements, methodologies, procedures and operation workflows, offering clear guidance for independent student operation.

After completing video learning, students access the virtual experiment program to learn the purpose and significance of the experiment and complete preparatory tasks, including introductions to instrument names, principles and functions, experiment fundamentals and safety training, thereby consolidating theoretical and safety foundations for hands-on operations.

The experimental operation follows standardized full-process steps: launch data acquisition software and complete zero-point calibration; activate the throttle cone control program and lubricating oil supply device; switch on the motor power and start the frequency converter. After equipment startup, adjust the throttle cone position to collect data. After measuring one rotational speed, modify the frequency converter to test subsequent speeds until all operating conditions are completed. During operation, key experimental phenomena need to be observed: under stall conditions (rotational speeds N1, N2), fine-tune the throttle cone to capture near-stall states, observe and record hysteresis loop effects when exiting stall. Under surge conditions (rotational speed N3), adjust the throttle cone slightly to observe airflow oscillation and follow the surge exit operating procedures to ensure experimental safety. Upon completion of all tests, shut down all experimental equipment per standard procedures to finish the operation workflow. After operations, the system automatically scores students based on operational standardization and supports data export for subsequent analysis. Finally, students submit experiment reports offline to complete the full teaching closed-loop, which spans from theoretical learning and virtual operation to data review.

3.2. Application of model-driven design in aviation radiators

Aviation environmental control systems are critical airborne systems that guarantee a safe environment for crew and onboard equipment. As core components, radiators undertake heat dissipation to maintain stable and reliable system operation, and their performance directly determines the normal function of environmental control systems. The assembly welding of radiators requires precise fitting of multiple parts, so dedicated welding fixtures must be designed to guarantee welding quality and production efficiency.

At present, most domestic manufacturers of aviation environmental control systems design radiator assembly welding fixtures using 2D drawings [8]. The workflow starts with receiving 2D drawings of radiator product models. Based on these drawings and assembly welding process requirements, designers retrieve reference drawings of similar radiator welding fixtures. After obtaining reference drawings, designers manually revise dimensional parameters of fixture components one by one to match the clamping requirements of the target radiator. After dimension modification, designers perform a clamping compliance inspection: if the fixture fails inspection, designers return to adjust component dimensions and recheck; if compliance is met, fixture design is finalized, resulting in deliverable design drawings for production. This forms a standardized closed loop of "receiving drawings – retrieving references – dimension modification – inspection and finalization".

Liu et al. constructed a model-driven variant design system for radiator assembly welding fixtures of environmental control systems [9]. Centered on model-driven logic, the system workflow proceeds as follows: the operator opens the radiator model in the Teamcenter platform and invokes the fixture variant design module to retrieve the master model. If retrieval fails, build and archive a new master model via NX modeling; if successful, directly invoke the existing master model. After loading the master model, the system reads radiator clamping features and process attributes, reassigns parameter expressions to drive the variation of the master model, rapidly assembles radiators and fixtures, and saves the new fixture to a designated file path. After fixture design is finished and submitted for review, the rapid drawing generation module can be activated to batch export drawings for selected components to a specified directory, completing the new fixture design. This realizes efficient and streamlined variant design of radiator fixtures.

4. Conclusion

Focusing on digital modeling and simulation of typical aircraft control objects, this paper systematically sorts out their cross-domain coupling characteristics and core technical demands. It clarifies that digital twin and model-driven design are key approaches to overcoming the limitations of traditional single-domain modeling and improving modeling precision and simulation efficiency. Research shows that the five-layer architecture of digital twin (physical entity layer, virtual model layer, service application layer, communication network layer, data fusion layer) enables full-lifecycle dynamic mapping and virtual-physical interaction of aircraft control objects. Model-driven design effectively balances model complexity and accuracy, supporting multi-domain coupled modeling and rapid iterative optimization.

Currently, digital modeling of typical aircraft control objects still faces prominent challenges: difficulties in precise characterization of multi-domain coupling relationships, trade-offs between simulation efficiency and accuracy, and an imperfect model verification system. Future research should focus on breakthroughs in core technologies including multi-physics coupled modeling, dynamic closed-loop interaction and intelligent decision optimization, to build a high-precision, high-reliability and high-efficiency digital modeling and simulation system. This research can provide solid technical support for upgrading the design level of aircraft control objects, safeguarding flight safety and advancing the digital transformation of China's aviation industry.

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