Research on Design Method of Human-in-the-loop Civil Aircraft Simulation System

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Abstract. In the process of aircraft development, in the conceptual design and functional design phase before semi-physical simulation verification, it is often necessary to rely on the all-digital simulation system to design aircraft components and systems and verify that all requirements are satisfied. To meet the civil aircraft design requirements under unconventional conditions and build a holistic and comprehensive functional network, this paper demonstrates a forward design process of the scene-based civil aircraft system functional requirements identification based on the human-in-the-loop simulation system. The method proposed in this research promotes the construction of a requirement-function evidence chain. It provides a theoretical basis and method suggestions for the transformation from result control to process guarantee to support the development of civil aircraft products.

1. Introduction

In the process of aircraft development, in the conceptual design and functional design phase before semi-physical simulation verification, it is often necessary to rely on the all-digital simulation system to design aircraft components and systems and verify that all requirements are satisfied.

The flight accident is not only caused by the pilot's mistakes but often caused by many potential factors. However, accidents are small-probability events, and the risks and costs of experimental research are substantial, so it is impossible to provide sufficient data for research work. Therefore, it is necessary to establish a human-in-the-loop digital simulation model to simulate these situations.

The most commonly used in the development of civil aircraft and systems is the system engineering double V model describing the development of aircraft systems (double V refers to Validation & Verification), as shown in figure 1 [1-3]. In this figure, the right side of the double V model describes the traditional bottom-up system design process, covering the various stages of integration of unit testing, individual different module testing, molecular system testing, and final
system acceptance testing. The left side of the double V model is the top-down design flow from the requirements, the analysis of system functions, the completion of the design synthesis phase, and the final software implementation and unit testing of the software analysis design [4,5]. The civil aircraft-level functional requirements identification and confirmation activities are the basis for constructing the system-level requirements of civil aircraft products.

Figure 1 Double V process diagram under system engineering (Validation & Verification)

Given the shortcomings of traditional document-based system engineering methods in civil aircraft development engineering practice, this paper introduces model-based civil aircraft functional requirements identification and confirmation methods [6,7]. To reflect the functional complexity required for method analyzing and process identification, we select a typical civil aircraft operation scenario "take-off wind shear and escape" as an example to demonstrate the functional requirements identification and confirmation methods.

2. The design method of human-in-the-loop civil aircraft function simulation system

2.1 Human-in-the-loop system
The human-in-the-loop model is a complete representation of the pilot's mission process. The model not only dynamically interacts with the external environment but also expresses the thinking and decision-making mechanism of the pilot information processing process. However, there is currently no completed human-in-the-loop model. There are two main reasons. 1) the randomness and the individual differences of the human body are not only reflected in the anthropometric data but also reflected in the microscopic thinking of human beings. This process has made it difficult for humans to obtain microscopic cognitive mechanisms, especially the professional environment of pilots. The working environment is continuously changing, requiring pilots to have good adaptability. 2) It is hard to analyze the pilot's cognition and manipulation data in detail because a flight accident occurs rarely. During the study, the lack of flight data from the pilot under normal conditions made it challenging to obtain the pilot's cognitive and manipulation rules. In the aviation field, pilot quality control models are used to evaluate flight quality.

2.2 Civil aircraft functional requirements identification and design process
The Model-based System Engineering (MBSE) method is a commonly used method in the modeling process of complex systems [8-10]. It uses an agreed system modeling language (such as UML/SysML, etc.) to model the process of building a system form requirement level to function level. And finally build a concrete, visual model of system functional structure.

The above process is described by the MBSE method, which corresponds to the modeling of the requirements-function logic solution through the functional black box. The necessary process of
constructing a function black box is: by constructing a black box activity diagram (BAD), identifying functional flow and functional interaction for critical functional use cases, including the activity of the use case role into the model, and constructing a scenario based on the use case activity; extracting the black box sequence diagram (BSD), based on the use case scenario, traversing all scenarios of the system with multiple sequence diagrams, covering all activity diagram behaviors, clarifying all interactions with the use case roles; identifying preliminary requirements and function lists.

3. The human-in-the-loop civil aircraft simulation model

3.1 Human-in-the-loop system based on the control model

The complete human-in-the-loop model should consist of three parts: the simulation environment part, the pilot simulation model, and ground control. In the research of human-in-the-loop system engineering, people pay great attention to the research of the human control model and use the human control model to conduct overall analysis, evaluation, and design of various human-machine systems. In the aviation field, pilot quality control models are used to evaluate flight quality. In this paper, we focus on the function design and use the flight trajectory of the aircraft in a specific scene as the evaluation basis for the functional design. Therefore, we simplify the pilot simulation model to the control model and ignore the cognitive process and the anthropometric part of the pilot.

3.2 Pilot model design

According to the flight dynamics, the torque and force on the aircraft determine the motion of it. The pilot manipulates the rudder, elevator, aileron, and throttle of the aircraft through human-machine interaction equipment inside the cabin to achieve the purpose of controlling the movement of the aircraft by changing the forces and moments acting on the aircraft. At the same time, the human-in-the-loop model research shows that the vast majority of controllers involved are uncertain and time-delayed [11]. In the control process of the wind shear escape, the deviation between the pilot's final action and the expected action is inevitable. Therefore, in the task of performing the wind shear escape, the flight trajectory will be different at each time. In the present study, we consider that the pilot's input amount at time t is designed to mean the pilot's operational time-lag characteristic. Because of the small error randomness of the pilot during operation, the pilot's manipulation error can express by a normal distribution. On the other hand, the pilot's interaction with the aircraft in the cockpit system covers the visual effect of the pilot's environment from outside the cockpit, the state of the aircraft, the physiological perception of the pilot, the visual feedback of the instrument system, the force feedback of the joystick, and information feedback of the cabin acoustic signals, etc. Therefore, a practical human-environment loop system framework will better reflect the pilot's feedback on the aircraft's function during the wind-shearing process, as shown in figure 2.

![Figure 2 Human-in-the-loop system frame diagram](image)

In addition to the pilot's operational error having a time-dependent hysteresis under the normal distribution, the pilot has an unavoidable hysteresis based on experience and aircraft parameters to determine whether wind shear occurs. The pilot's warning action is triggered only when the aircraft
parameters change, or the rate of change exceeds a certain level. Therefore, when designing the pilot model's response to the wind shear response, the pilot should judge the delay effect of the wind shear. In this study, consider the pilot's input at time $t$ as

$$P(t, \delta) = e^{-\tau t} P_{\text{expect}}(t, \delta) + \Delta P(t, \delta)$$  \hspace{1cm} (1)$$

It shows the pilot's operational time lag characteristics. Also, due to the small error randomness of the pilot during operation, the pilot's manipulation error can be represented by a normal distribution, which is

$$\Delta P(t, \delta) = (2\pi\sigma)^{-1/2} \exp(-\delta - \mu)^2 (2\sigma^2)^{-1}$$  \hspace{1cm} (2)$$

In the emergency state, the distribution of the aircraft's input from the pilot model will be converging.

4. Civil aircraft function identification

4.1 Civil Aircraft Functional Requirements Identification and Functional Design

The process of identification of civil aircraft function requirements is firstly defining functional requirements according to user requirements, then recording functional logic/physical architecture descriptions, and finally confirming and verifying requirements. Through the requirements analysis, the process first defines the top-level requirements and constraints for the realization of aircraft products and further refines the black box for the requirements description, the functional analysis, and the capture of the requirements. The black box is decomposed to the system level, forming the interface requirements to ensure the integrity and correctness of the entire design process.

Based on the essential functions combined with engineering experience and related technical principles, the Use Case is used as the basic unit to identify the relevant roles of the primary functions. It is the core difference between modeling requirements analysis and documented requirements analysis. In the requirements-function chain modeling process, this study selected the Rhapsody tool as the modeling platform, which has a windowed modeling interface and rich practical functions and has a data interaction interface with Matlab/Simulink platform.

Figure 3 fully describes the design flow of the process and the analysis results corresponding to each node. Among them, the part of black box detachment design as a highlight differs from other requirements identification literature, complements the verification function allocation and perfect requirements capture. It provides a reference for system function analysis.

4.2 Scenario-based requirements identification case

Taking the low altitude wind shear as an example, by investigating the pilot's operation standard manual and the local machine standard operation steps, we can conclude the top essential requirements about the use case of wind shear escaping during taking off.

According to different stages of the take-off process, the scene of wind shear during take-off can be subdivided into five aspects: the aircraft slipping out, the runway acceleration, the ground climb, the wind shear escape, and retracting the landing gear. After the pilot determines to start the wind shear
escape operation, the case of wind shear escape can be divided into the three sub-case: adjusting the thrust, adjusting the climb rate, and adjusting the pitch angle. Figure 4 is a sub-case diagram showing the fundamental requirements of the aircraft function included in the wind shear.

After completing the design of the use case, the build activity diagram describes the workflow in the sub-case of wind shear escape to present the specific requirements of the functional requirements at the pilot level. It visually expresses the interaction between the operating environments. Based on the use case diagram, combined with the use case behavior analysis, a functional black box activity diagram (BAD) of the sub-case "wind shear escape" is formed, which shown in figure 5. Figure 5 shows the program of how the aircraft escape from the wind shear immediately during take-off. When the pilot judges that the wind shear occurs according to the aircraft parameters, the pilot enters the wind shear escape program. When the wind shear is changed, the pilot increases the thrust of the aircraft to the maximum, increases the climb gradient, and maintains the wing to stabilize the fuselage; after confirming that the wind shear escaped, the aircraft accelerates and climbs to complete the take-off process.

The functional black box sequence diagram (BSD) relies on specific use cases to represent the scene. A sequence diagram consists of a character, a vertical lifeline of a module, and a set of information that passed in order along a specific time. The flight control system receives the take-off command from the pilot and enters the taxi acceleration phase. The flight control system detects that the aircraft speed has reached V1, adjusts the flap control to change the pitch angle. At this time, the aircraft flight parameters are detected to be abnormally changed, and the wind shear is confirmed. The pilot increases the thrust and the rate of climb, then escape from the wind shear. After the pilot keeps the thrust and climbs state away from the wind shear zone, accelerate the climb into the standard flight profile and complete the wind shear escape operation, as shown in figure 6.

The BAD diagram implies the dependence between functions. With this relationship, we can mine the missing part of the requirements design in the white box analysis, which provides the basis for the iterative design. Derived from the function flow link (L) and The function flow element (E), we can derive a sequence diagram that can traverse the activity map. The sequence diagram covers all activity diagram behaviors. It clarifies the interaction between all use case roles and captures related design requirements through analyzing the logical solutions (L) and concrete solutions (P) implemented by
the functions. Taking the links L1, L2, and E3 in figure 6 as an example, the results of the corresponding functional structures captured through the requirements are shown in the following table.

| Table 1 Example: Function (AF) Capture Function Requirements (AFR) in sub-case Cases |
|---------------------------------|---------------------------------|---------------------------------|
| **E1 (Human-Machine Interface)** | **E2 (Manipulation Interface)** | **Element 3 (Control System)** |
| Function flow Link/Element | The human-machine interface waits for the command from the crew. | The man-machine interface outputs the maneuver command to the flight control system. | The flight control system executes the maneuver command to make the aircraft detach from the wind shear. |
| Functional Requirements Identification | Multi-manipulation interface design compliance | Normal climb state to emergency climb state switching | The aircraft quickly adjusts its posture and climbs steadily in an environment where the wind field changes drastically. |
| Logical solution | Staged mode manipulation | Different control laws for each manipulation mode | Designed to ensure robust aircraft control under severe conditions |
| Physical solution | Different climbing states correspond to different maneuvers | Requires absolute handling precision and steering stability | System architecture redundancy design to improve the robustness of operating conditions |

5. Civil aircraft system human-in-the-loop numerical simulation

5.1 Function Simulation Module
This section bases on the functional black box activity model built in the previous section. Through the numerical simulation method, the functional requirements of the aircraft black box transform into the trajectory target in the white box model architecture. The virtual verification machine simulation method verifies the effectiveness of the aircraft function design in coping with the expected scenario and iteratively refines the functional structure of the functional requirements and response.

For the corresponding requirements captured in the previous analysis, the established model should meet the corresponding logical solution and implement its reliable solution. For the compliance requirements of multi-manipulation interface design, it is proposed to design multiple sets of pilot control logic. Each control logic corresponds to a flight scenario. Decouple the control mode from different flight conditions or design different control rules or parameters for different control modes can be optional, too. And finally, we can integrate different control modes into a set of switching systems to realize the need for switching from the normal state to the emergency state command for the aircraft. In terms of control robustness under severe conditions, in addition to applying robust control in the design, redundant architecture can be added to ensure control stability at the flight safety level.

5.2 Functional behavior numerical simulation
This simulation case uses the characteristics of the body, aerodynamic parameters, aerodynamic torque parameters, etc. based on the Boeing 747-400 cruise conditions provided in the classic literature[12].

Different wind shear types, such as increased performance wind shear, decreased performance wind shear, increase before decrease performance wind shear, are shown to increase or decrease the lift force at different horizontal distances. Taking the increase before decrease performance wind shear into an example, when the aircraft enters the downburst area, the airspeed of the aircraft increases, and the lift increases; when it crosses the upwind area, it enters the downwind area, the airflow changes, and the plane encounters a downwind. When the flow blows, the airspeed of the aircraft reduces, and the corresponding lift weakens. According to the analysis of the influence of different wind shear
types on the aircraft, it can abstract into the impact of the aircraft on the lift, which reflected in the control input is the corresponding interference signal on the lift input, as shown in figure 8 below.

Figure 7 The simulation signal input for simulating different wind shear types

Figure 8 Longitudinal track simulation curve in the state of the transverse heading attitude

Combining the pilot's control logic of the aircraft with changes in the external environmental parameters of the aircraft, figure 8 shows the resulting flight curve. The aircraft initially sets to take-off from the ground. The whole process can be described as below: Starting the wind shear escape operation after encountering the wind shear, increasing thrust and the climb rate to maintain the flight state, and finally realizing the wind shear escape operation. In the experiment, the standard climb curve was set to simulate the desired flight profile. Wherein, the X-axis represents the flight distance, and the Y-axis represents the vertical height.

It can see through the simulation curve that the effects of different types of wind shear during the take-off of the aircraft are different. In the increased performance wind shear, the flight altitude increases sharply in a short period due to the sudden increase of lift; if the wind shear reduces, the downstream airflow will abruptly decrease after a certain period of height increase. However, no matter what type of wind shear encountered, increasing the thrust and increasing the climb rate are the safest choices. The timing of performing the correct operation becomes a critical factor in preventing accidents caused by wind shear during take-off.

After the numerical simulation, we found that the process of “encountering the take-off wind shear and escaping from it” lacks the identification of wind shear type and judging the timing of encountering wind shear, thus affecting the effect of wind shear treatment. And should increase wind shear. The early warning and diagnosis links, that is, the aircraft should add the functions of pre-treatment behavior and protective behavior under abnormal conditions, which provides the pilot with timing judgment advice and operational guidance. More specifically, when the climb height changes drastically or abnormal fluctuation occurs, the wind shear warning should be triggered. The aircraft should prompt to increase the engine power and climb rate, and issue a safety warning to the pilot to shorten reaction time. It can conclude that the corresponding subsystem should realize the functions of screening of wind shear and the early warning of danger during take-off.

6. Conclusion

This paper uses a scene-based human-in-the-loop simulation system as a demonstration framework. After analyzing the critical original functional requirements of the civil aircraft functional requirements architecture under a specific scenario, and confirming the integrity and correctness of the requirements, we finally realized structuring and modeling the requirement-function logical chain. This paper uses the civil aircraft "take-off wind shear escape" scenario as a research case, showing the following modeling process:

- Starting with the high-level requirement identification related to the task scenario based on the Rhapsody platform, the primary functional requirements are confirmed by analyzing the use case behavior in the scenario. Then construct the functional activity diagram and the sequence diagram. Following the path of how to implement the functional requirements, we analyzed the logical and
physical solutions of function implementation and captured the corresponding functional requirements.

- We confirmed the correctness of the requirements by setting up the state machine and the integrity of the requirements based on the use cases;
- To improve and realize the iteration of function capture, we construct the human-in-the-loop model based on Matlab/Simulink platform. By confirming whether the functional behavior meets the relevant requirements through simulation and capturing the derivative requirements, we build the foundation for analyzing the intrinsic link between system-level functional requirements and the human-in-the-loop system design.

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