Development of Engine Electrical Control Experimental Platform Based on Virtual Real Interaction

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Abstract: To improve the operability and visualization of engine electrical control system course experiments, a virtual real interactive engine electrical control experimental platform is developed. Based on SOPC technology, an engine controller and hardware simulation system are constructed. Labview is used to develop a control interface for simulating cockpit engine control and display. SolidWorks is used to design a virtual model of the engine and then achieve assembly and follow-up in the upper computer. A proportional engine model is developed by imitating the actual external dimensions and electrical accessory layout of the engine to achieve the acquisition of key engine parameters and simulation of the action of the actuating components. Through multiple rounds of experimental verification, the platform can accurately reproduce the engine electrical control logic, and the experimental data curve is consistent with the real engine parameter curve.

Keywords: Virtual Real Interaction; Virtual Model; System on Programmable Chip (SOPC); Engine Start Control; Engine Power Control

1. Introduction

The course on electrical control systems for aero-engines is a core subject within aeronautical electrical engineering, particularly designed for students in non-aeronautical propulsion disciplines. This course is structured on the foundational knowledge and cognitive characteristics of electrical engineering students and employs an integrated approach that blends electrical drive control with engine control. This method is delivered through a combination of online and offline virtual-real teaching techniques [1]. Laboratory experiments are a crucial part of this curriculum. In its earlier iterations, the course relied on Computer-Based Training (CBT), where students followed preset steps within a presentation to operate and understand engine electrical control logic. However, purely virtual operations fell short in fostering a deep understanding of this logic and its analytical processes. With the rapid progression of virtual reality technology, the integration of virtual-real experiments and virtual simulation experiments [2-5] has become increasingly prevalent across various scientific and engineering fields. This technological advancement has led to the development of both purely virtual simulation projects and semi-physical virtual simulation projects tailored for educational and experimental purposes. These projects have significantly enhanced the interactivity, practicality, and innovative potential of the course's teaching and experimental activities.

In the development of the experimental platform, extensive research was conducted on SOPC-based engine control [6,7], engine electrical control logic [8-13], and upper computer systems for operation and display using Labview. Analogies were drawn between different control systems, such as comparing pressure regulation valves to three-terminal voltage regulators, and likening hydraulic, pneumatic, and electrical circuits. Furthermore, the relationship between fuel control and thrust control in turbine engines was analogized to the current loop and speed loop in a dual closed-loop speed regulation system for electric motors. Through this comprehensive approach, the electrical control of aero-engines is effectively reproduced on a virtual-real interactive experimental platform. This platform enables students to build a comprehensive knowledge framework centered around electrical systems while encompassing mechanical, hydraulic, and pneumatic components.

2. Overall System Design

The overall structure of the virtual-real integrated engine electrical control experimental platform is shown in Figure 1. This platform uses an FPGA processor as the control core, facilitating interaction between the simulation platform and the upper computer system through the electrical control platform and a proportional engine model. It enables the simulation of engine controller logic, including engine start, thrust control, and reverse thrust control.

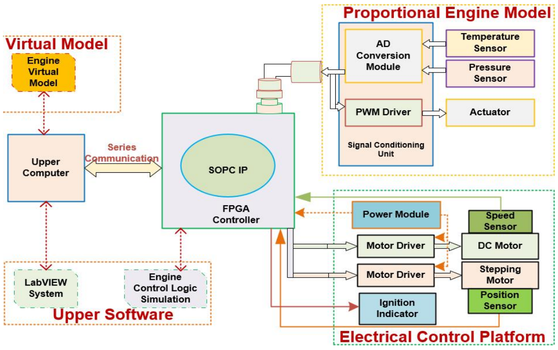


Figure 1. Overall System Design

The FPGA processor interacts with the upper computer, electrical control platform, and proportional engine model to handle data exchange, including receiving control commands, processing logic, and outputting instructions. The electrical control platform simulates the operational states of components such as engine speed, solenoid valves, actuators, and ignition exciters. The lower computer software implements engine control processes and simulates engine control logic through control algorithms and principles. Meanwhile, the upper computer software communicates with the lower computer via a serial port to send control commands and receive feedback sensor signals, enabling engine control and parameter visualization. A virtual model of the engine is created using SolidWorks software, which designs 3D components and establishes the degrees of freedom between parts. This virtual model is integrated into the upper computer software to achieve coordinated interaction. The proportional engine model is used in laboratory environments for collecting engine sensor signals, actuator operation, and signal transmission, while the virtual engine model is utilized for real-time visualization of engine operating conditions across all working states.

3. Hardware System Design and Implementation

3.1 Design of the Engine Electrical Control Simulation Platform

The electrical control platform comprises modules such as the processor, power supply, motor drivers, motors, solenoid valves, indicator system, speed sensors, and position sensors. Its system structure is illustrated in Figure 2.

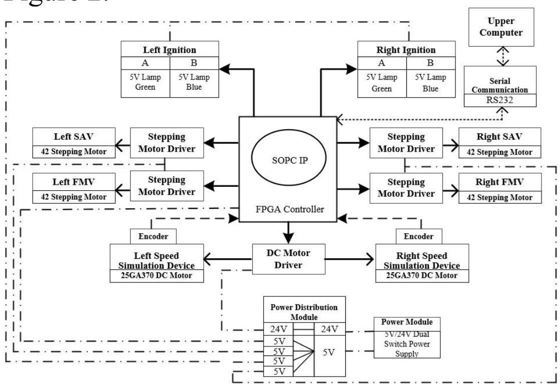


Figure 2. Structure of the Electrical Control Platform

The processor selected is the Cyclone III FPGA from Altera, which closely resembles the V2500 engine controller. The power module adopts a dual-switching power supply configuration, inputting 220V AC and outputting 5V and 12V DC, providing power to the processor, driver modules, and motors.

Two high-power, high-speed 25GA370 DC motors, paired with a dual-channel PWM motor driver module, are used to simulate the speeds of the left and right engines. Omron high-precision encoders are mounted on the rear of the motors to collect real-time DC motor speed pulses. This data is used by the processor to calculate motor speeds and provide real-time feedback to the upper computer, achieving closed-loop control of the motors.

The solenoid valve simulates the adjustable geometry valve opening of the engine, employing a 42 high-speed constant torque closed-loop stepper motor and an HBS57 high-performance closed-loop stepper motor driver set. An angle sensor is mounted on the drive shaft to monitor the stepper motor's rotation angle in real time, ensuring the accuracy of the valve opening. This platform uses four sets of stepper motors to simulate the

SAV and FMV openings for both the left and right engines.

The indicator system simulates the ignition exciter A and B channels, utilizing two sets of LED indicators controlled by TTL levels.

Through functional and performance analysis, device selection, and design, the hardware system structure adopted by this control platform are shown in Figure 3.

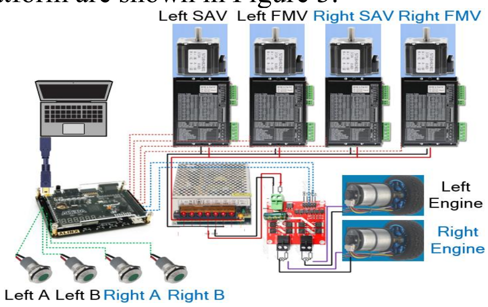
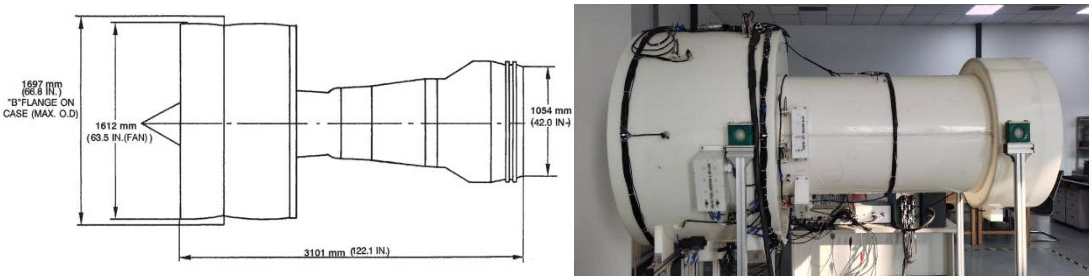


Figure 3. Hardware Components of Electrical Control Platform

3.2 Proportional Engine Model

The proportional engine model is based on the IAE V2500 prototype, constructed using high-strength PVC engineering plastic. The design closely mirrors the prototype in terms of exterior dimensions, crucial electrical accessories, and electrical wiring layout, albeit with proportional-down dimensions. The overall size is 2,325 mm in length and 1,209 mm in height, with a four-point support base measuring 2,188 mm in length and 280 mm in height. Sensors, actuators, and electrical cables are installed according to the layout. The appearance of the prototype and the physical model is shown in Figure 4. The electrical accessories installed on the model include temperature sensors, pressure sensors, ignition exciters, actuators, valves, solenoid valves, and electronic controllers.



a) Original Size of Engine b) Engine Physical Model

Figure 4. Proportional Engine Model

4. Virtual Engine Model

The virtual engine model provides an intuitive depiction of sensor and actuator actions during engine control processes, such as rotor rotation, ignition exciter status, and actuator position or angle changes. The model units are designed and developed using SolidWorks software, while assembly and operational control are implemented through Labview programming. As illustrated in Figure 5, the primary components of the model units include a fan, low-pressure rotor system, high-pressure rotor system, combustion chamber, fan casing, core engine casing, ignition exciter, air starter, and actuators.

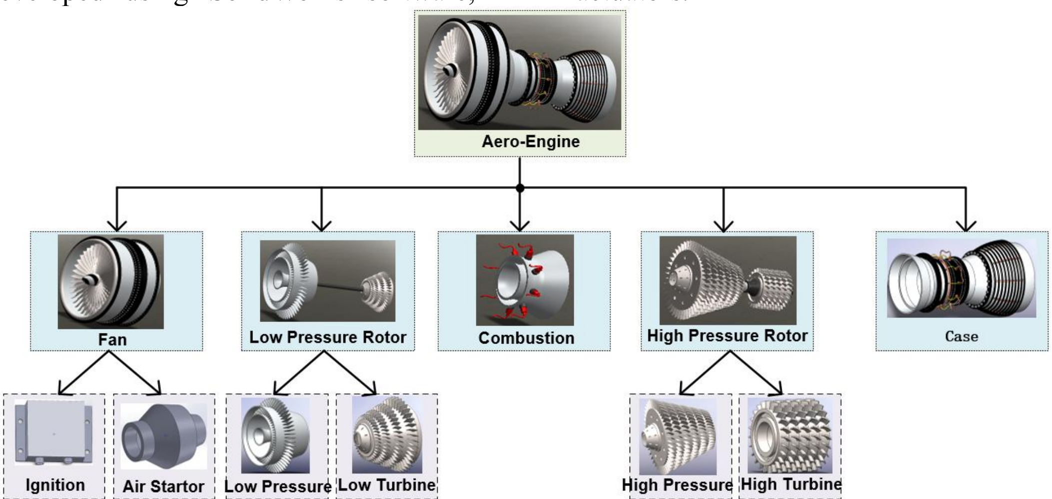


Figure 5. Structure of the Virtual Engine Model

The low-pressure rotor system consists of a low-pressure compressor and a low-pressure turbine connected by a low-pressure shaft, rotating under the propulsion of the low-pressure turbine. Its rotational speed is denoted by N1 or NL. The high-pressure rotor system, similarly, comprises a high-pressure compressor and a high-pressure turbine connected by a high-pressure shaft, rotating under the impetus of the high-pressure turbine, with its speed denoted by N2 or NH.

The combustion chamber is the core component where fuel mixes with air and ignites under the influence of high-energy igniters. This process converts thermal energy into mechanical energy, driving the engine's high-speed rotation. During engine startup and operation, the state of combustion within the engine is intuitively represented by the flame in the virtual model's combustion chamber.

The ignition exciter, located on the fan casing, indicates the operational status of channels A and B through color changes—green and blue—during the engine ignition phase.

An important monitoring parameter during engine start-up is the openness of the air starter valve. In the virtual model, the actual degree of openness is visually represented by the valve's rotation angle.

5. Software System Design

The software system is composed of two main components: the upper computer software, responsible for control and display, and the lower computer software, dedicated to engine control.

5.1 Upper Computer Software Design

The upper computer software is developed using LabVIEW and, as shown in Figure 6, is structured to perform the following core functions: engine start control, engine thrust control, engine reverse thrust control, engine parameter analysis, and the engine virtual platform. The engine start control serves to manage engine startup operations and simulate logic, while the engine power control simulates thrust logic under various conditions. The engine reverse thrust control simulates the logic of reverse thrust deployment during aircraft landing. These three control functions are operated and displayed through the cockpit control panel, throttle lever, engine parameter page, and virtual engine model. Interaction with the electrical control platform and the proportional model is achieved via serial communication.

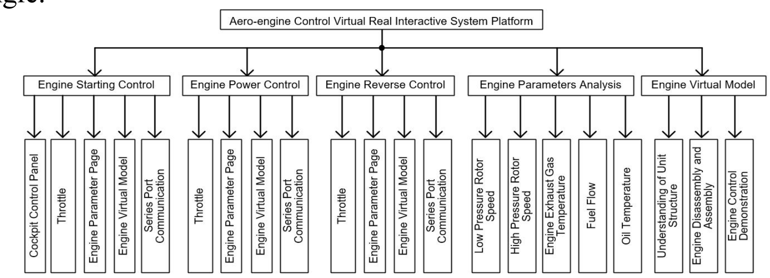
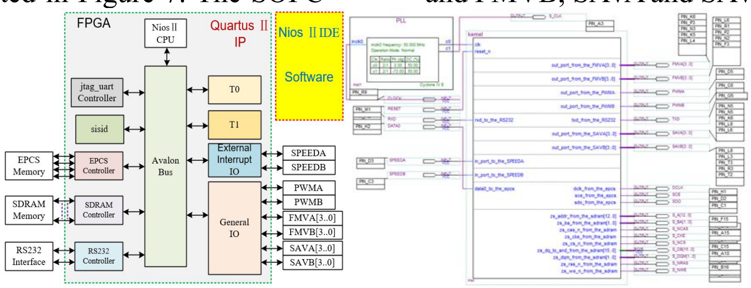


Figure 6. Structure of Upper Computer Software

5.2 Lower Computer Software Design

The lower computer software is built upon an FPGA-based SOPC core. This is implemented using Quartus II and Nios II software, with the architecture illustrated in Figure 7. The SOPC core comprises components such as the CPU, jtag uart controller, EPCS controller, SDRAM controller, RS232 controller, timers, external interrupt I/O ports (SPEEDA, SPEEDB), and general I/O ports (PWMA and PWMB, FMVA and FMVB, SAVA and SAVB).



a) IP Core of Engine Control b) Structure of SOPC

Figure 7. Core Architecture and Functional Principles

The lower computer software utilizes a modular programming approach, written in C and developed within the Nios II IDE. The process flow is depicted in Figure 8.

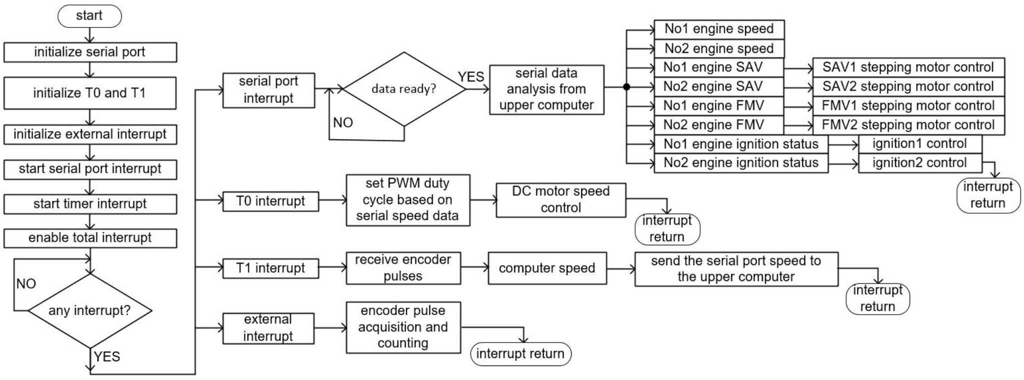


Figure 8. Flowchart of Lower Computer Software

The software design predominantly employs an interrupt-driven approach, including serial port interrupts, timer interrupts, and external interrupts. Serial port interrupts facilitate data communication between the upper and lower computers. When control commands and status parameters are sent from the upper to the lower computer, interrupt service routines parse the data to obtain engine speed, SAV positions, FMV positions, and ignition exciter status commands. These are used to control the DC motor, stepper motor, and the ignition exciter indicator respectively. Timer 0 Interrupt manages the DC motor control. It adjusts the PWM duty cycle based on the serially received speed commands, ensuring the DC motor speed meets the desired setpoint through closed-loop control. Timer 1 Interrupt calculates the DC motor speed by counting pulses within the timer period and transmits this information back to the upper computer for display via the serial port. Two external interrupts are utilized for capturing and counting pulses from the DC motor encoder.

6 Experimental Platform Testing

The experimental platform of engine electrical control with virtual real interaction is shown in Figure 9.

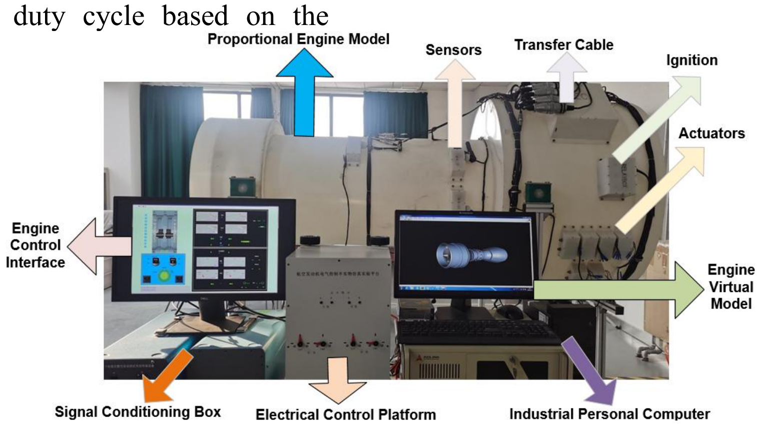


Figure 9. Composition of the Verification Experimental Platform

To verify the functionality of the experimental platform, the engine start control process is used as an example. The operation is simulated via the engine control interface, where the pilot initiates engine startup. The throttle lever is moved to the "IDLE" position, and the rotation mode selector switch is set to "IGN/START". At this point, the engine parameter display page automatically appears in the display area. The main handle of the left engine is then turned to the "ON" position, initiating the start-up of the left engine. Changes in engine parameters, electrical control platform simulation components, the virtual engine model, and the proportional engine model's electrical accessories are observed and recorded.

During the engine start simulation test, data is recorded from the completion of the engine start operation and as the N2 speed accelerates from 0. Three sets of experimental data using N2 as the reference point are shown in Tables 1, 2, and 3.

Table 1. First Experiment Record for the Left Engine

N2 Speed (%)	DC Motor Speed (RPM)	SAV Pointer	Virtual Model SAV Status	Proportional Model SAV Status	FMV Pointer	Virtual Model FMV Status	Proportional Model FMV Status	Igniter A	Igniter B	Simulated Ignition Device
0	0	From 0° clockwise to 90°	Open	Open	0	Closed	Closed	OFF	OFF	Not igniting
16	794	90°	Open	Open	0	Closed	Closed	ON	OFF	Igniting
22	1067	90°	Open	Open	From 0° clockwise to 90°	Open	Open	OFF	ON	Igniting
50	2498	From 90° counterclockwise to 0°	Closed	Closed	90°	Open	Open	OFF	OFF	Not igniting
58.3	2907	0°	Closed	Closed	90°	Open	Open	OFF	OFF	Not igniting

Table 2. Second Experiment Record for the Left Engine

N2 Speed (%)	DC Motor Speed (RPM)	SAV Pointer	Virtual Model SAV Status	Proportional Model SAV Status	FMV Pointer	Virtual Model FMV Status	Proportional Model FMV Status	Igniter A	Igniter B	Simulated Ignition Device
0	0	From 0° clockwise to 90°	Open	Open	0	Closed	Closed	OFF	OFF	Not igniting
16	788	90°	Open	Open	0	Closed	Closed	ON	OFF	Igniting
22	1092	90°	Open	Open	From 0° clockwise to 90°	Open	Open	OFF	ON	Igniting
50	2457	From 90° counterclockwise to 0°	Closed	Closed	90°	Open	Open	OFF	OFF	Not igniting
58.3	2983	0°	Closed	Closed	90°	Open	Open	OFF	OFF	Not igniting

Table 3. Third Experiment Record for the Left Engine

N2 Speed (%)	DC Motor Speed (RPM)	SAV Pointer	Virtual Model SAV Status	Proportional Model SAV Status	FMV Pointer	Virtual Model FMV Status	Proportional Model FMV Status	Igniter A	Igniter B	Simulated Ignition Device
0	0	From 0° clockwise to 90°	Open	Open	0	Closed	Closed	OFF	OFF	Not igniting
16	790	90°	Open	Open	0	Closed	Closed	ON	OFF	Igniting
22	1075	90°	Open	Open	From 0° clockwise to 90°	Open	Open	OFF	ON	Igniting
50	2479	From 90° counterclockwise to 0°	Closed	Closed	90°	Open	Open	OFF	OFF	Not igniting
58.3	2964	0°	Closed	Closed	90°	Open	Open	OFF	OFF	Not igniting

After comparing, it was found that the ratio of the actual speed of the DC motor to its maximum speed is consistent with the N2 speed ratio. Additionally, during three experimental trials, the speed deviation of the DC motor at various time intervals was controlled within 3%. The valve actions, igniter statuses, and combustion chamber ignition situations in the electrical control platform, virtual engine model, and proportional engine model were consistent with the real engine startup process. The startup logic curve is depicted in Figure 10. The experimental results demonstrate that the platform can accurately reproduce the engine startup control logic.

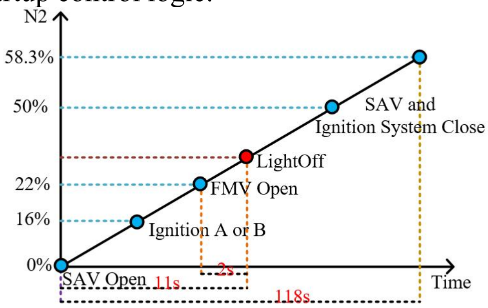


Figure 10. Engine Startup Control Experimental Logic Curve

Multiple comparative experimental analyses were conducted on the platform's power control, reverse thrust control, and engine parameter analysis functions. Comprehensive validation of the platform's capabilities and performance was performed through upper computer control, lower computer calculations, electrical control platform simulation actuation, virtual engine model follow-up, and proportional engine model data collection and actuation. The experimental results were consistent with the real engine control laws.

7. Conclusion

The experimental platform developed in this study is tailored for non-aerospace power disciplines. It aligns with the knowledge structure and cognitive characteristics of electrical engineering students by drawing multi-level analogies between electrical drive control and engine control, comparing hydraulic and pneumatic circuits to electrical circuits, and relating the fuel control and thrust control in a turbine engine to the current loop and speed loop in a dual-loop motor control system. This comprehensive approach constructs a multi-faceted knowledge framework for students, centered around electrical systems but inclusive of mechanical, hydraulic, and pneumatic elements. Experimental results demonstrate that the platform can intuitively replicate the electrical control logic, and control and actuation processes of a real engine, with the control outcomes aligning accurately with the actual engine control curves.

Acknowledgement

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