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Development of Virtual Simulation Platform for Automatic Flight Control Based on Unity3D

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Abstract: In order to visualize the relationship between flight control system and aircraft motion state, a virtual simulation platform for automatic flight control is developed based on the creation engine Unity3D. Firstly, a platform design scheme based on numerical calculation and Unity3D is proposed. Then, according to the theoretical teaching content, the mathematical models for typical longitudinal and lateral motion control modes based on state space are established, and the corresponding numerical solution algorithm is designed. At the same time, the interface between numerical solution algorithm and Unity3D, and the human-machine interface is developed according to the requirements of experimental teaching. Finally, the visualization and online virtual simulation of automatic flight control experiment are realized by deploying the designed platform on the school exhibition platform. The application of experimental teaching shows that the designed platform is helpful for students to be familiar with automatic flight control, as well as facilitate the sharing of teaching resources and improve the teaching effect.

1. Introduction

In order to ensure the flight safety, the flight control system of modern civil aircraft has a complex structure with many control modes, and involves different flight parameters. Relying solely on course theoretical teaching, it is difficult for students to associate specific flight control systems with changes of aircraft motion states, and appropriate experimental teaching is needed [1]. Single command-response method is widely applied in traditional experimental teaching for automatic control principle, and this method is difficult to meet the needs of students majoring in aircraft maintenance engineering to understand flight control principles and be familiar with flight control systems. Meanwhile, although experiments based on the maintenance simulator can help students become familiar with the flight control system [2], it is difficult to visualize the process and control effects of flight control design, and it is expensive and difficult to carry out sharing of teaching resources. Moreover, in the construction of virtual teaching and research section across schools, sharing resources such as experimental projects is the top priority [3], and relying on information technology to build sharing experimental resources has become the preferred way.

The approach applying visualization technology to experimental teaching can visualize experimental results and effectively deepen students' understanding of abstract concepts [4]. Nowadays, the visual experimental development scheme for flight control can be roughly divided into three types: (1) Based on Matlab and animation platform [5]. This solution adopted the same idea as the experiment of automatic control principle. Based on single input and single output to visual changes of single command-response, the method is simple to implement. However, its visualization effect is relatively stiff, and it is of limited help for students to understand the flight control principles and systems. (2) Based on commercial simulated flight software, such as FlightGear, Flight Simulator X, etc. [6]. This solution has good visualization effect, but it requires multiple software collaboration. Meanwhile, it is difficult to develop personalized experimental scenarios, and it is impossible to develop a human-machine interface with complex logical structures. (3) Based on three-dimensional rendering engines, such as OpenGL, Direct3D, Vega, etc. [7]. This solution has a good visualization effect, but it requires designing a large amount of underlying code, which is difficult to develop. All of the above three solutions are difficult to provide online testing and to share teaching resources.

Under the strong promotion of virtual simulation teaching by the Ministry of Education of China [8], modern information technology has been increasingly widely used in experimental teaching. In recent years, many excellent online virtual simulation projects have been developed for online experimental teaching without time and space constraints. Most of these projects are based on the creation engine Unity3D and are used in experimental teaching in different courses, such as satellites [9], robots [10] , UAV and its control [11] [12]. These projects focus on visualizing control effects and understanding control principle, rather than the composition of control systems.

To solve above-mentioned problems and combine with online virtual simulation requirements, a virtual simulation platform for automatic flight control is developed with satisfying flight control principle, flight control mode, flight control law design and control effect visualization requirements. The platform is based on numerical calculation and Unity3D, and can meet the needs for systematic experimental teaching and sharing of teaching resources.

2. Design Scheme of Virtual Simulation Platform

The requirements of flight control experimental teaching is to reproduce airborne flight instruments, inside and outside viewing angles, control parameter settings, flight parameters and aircraft motion state changes. With flight visual materials modelled by three-dimensional modelling tools 3D MAX, the requirements can be satisfied by comprehensively utilizing Unity3D components driven by relevant flight parameters. [13] Integrate all links required for the automatic flight control experiment in Unity3D to achieve the purpose of visual virtual simulation.

In all, the focus of visual virtual simulation is to obtain and display flight parameters. Flight parameters represent the actual flight motion characteristics and are obtained by solving of the mathematical model of the aircraft [14]. According to the relationship between mathematical model solution method and Unity3D, there are three different ways [12]: (1) Calling the model solution software written in a high-level language. It can freely set the aircraft dynamics model and parameters. The interface between software and Unity3D is simple. However, development is difficult and debugging is heavy; (2) Calling existing numerical calculation software to solve the model, such as Matlab. It can freely set the aircraft dynamics model and parameters, and it is easier to develop and the calculation results are accurate. However, the interface between software and Unity3D is complex, and it is extremely inconvenient for sharing teaching resources and online application; (3) Calling the physical model provided by Unity3D. It does not require the establishment of the aircraft dynamics model and the development of model solution software, which is directly convenient. However, it cannot correspond to the aircraft dynamics model adopted in theoretical teaching, and it is difficult to support theoretical teaching's explanation of flight principles and flight control design. To sum up the above analysis, the first way is adopted.

The design scheme of virtual simulation platform is shown in Figure 1. The platform is consisted of Unity3D part and high-level language program part. Among them, Unity3D part is responsible for the following works: viewing simulation of airborne flight instruments, aircraft motion states, etc.; reception of experimental parameter settings, switching control modes and display of flight parameters; save of experimental parameters and flight parameter changes. Three functional modules need to be developed: (1) a human-machine interface for experimental management and control; (2) a working mode that forms mathematical models to be solved; (3) an algorithm interface for parameter transfer with numerical solution algorithms. High-level language program part implements a numerical solution algorithm, which is responsible for solving the formed mathematical model and transferring calculated flight parameters to Unity3D part for visualization.

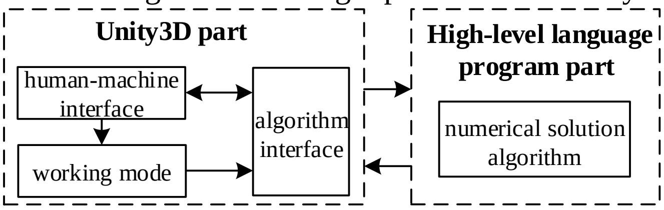

Figure 1 Design scheme of virtual simulation platform for automatic flight control

3. Mathematical Model and Solution Algorithm

Visualization is based on flight parameters, and the flight parameter values come from the solution of the aircraft mathematical model. Therefore, a unified mathematical model that can describe different flight control modes is needed. Two types of models including transfer function and state space are often used as mathematical model. Compared with transfer function, state space can better describe the flight characteristics. Moreover, it is easier to be solved and obtain various flight parameters, and respond timely to setting change. Thus the model based on state space is used.

3.1. Aircraft Mathematical Model Based on State Space

The flight control design concept of modern civil aircraft is to divide the movement of the aircraft into reference motion and disturbed motion. According to whether the change in the state of motion caused by the six degrees of freedom of the rigid body movement is limited to the symmetric plane of the aircraft, the movement of the aircraft can be divided into longitudinal motion and lateral motion [15]. Both longitudinal and lateral motion equations can be modelled into the form of state space:

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u} \tag{1}$$

where, $\boldsymbol{x}$ is the state vector of the system, composed of corresponding flight parameters; $\boldsymbol{u}$ is the input vector of the system, composed of input parameters that can be controlled by the driver and influence force and torque distribution; $\boldsymbol{A}$ is the system matrix, representing states mutual influence;

$\boldsymbol{B}$ is the input matrix, which represents the effectiveness of the input. For detail aircraft mathematical models, please refer to the literature [15].

3.2. Numerical Solution Algorithm

From the calculus theory, analytical solution of equation (1) can be obtained when the model parameters of equation (1) are fixed [16]. However, the model parameters of equation (1) change under different flight states and control modes, so only numerical solutions can be used to solve equation (1). After applying the numerical solution method, students can arbitrarily set parameters related to flight control during the experiment, so as to better simulate the real situation.

In order to ensure the reliable operation of the experimental platform, a fixed-stepsize numerical integral algorithm with relatively high accuracy is selected: fourth-order Longge-Kuta method. Before applying the fourth-order Longge-Kuta numerical integral algorithm, the state initial value and input initial value are required to be known. At this time, equation (1) can be expressed as:

$$\begin{cases} \dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x},\boldsymbol{u},t) \\ \boldsymbol{x}(t_0) = \boldsymbol{x}_0 \\ \boldsymbol{u}(t_0) = \boldsymbol{u}_0 \end{cases} \tag{2}$$

where, t_0 is the initial time, $\boldsymbol{x}_0$ is the initial value of the state vector, $\boldsymbol{u}_0$ is the initial value of the input vector, and $\boldsymbol{f}(\boldsymbol{x}, \boldsymbol{u}, t)$ is a function of time t, input vector $\boldsymbol{u}$ and state vector $\boldsymbol{x}$.

When step size is chosen as T, a standard fourth-order Longge-Kuta equation is written as:

$$\begin{cases} \boldsymbol{x}_{k+1} = \boldsymbol{x}_k + (\boldsymbol{y}_1 + 2\boldsymbol{y}_2 + 2\boldsymbol{y}_3 + \boldsymbol{y}_4)\cdot T/6 \\ \boldsymbol{y}_1 = \boldsymbol{f}(\boldsymbol{x}_k, \boldsymbol{u}_k, t_k) \\ \boldsymbol{y}_2 = \boldsymbol{f}(\boldsymbol{x}_k + \boldsymbol{y}_1\cdot T/2, \boldsymbol{u}_{k+1/2}, t_k + T/2) \\ \boldsymbol{y}_3 = \boldsymbol{f}(\boldsymbol{x}_k + \boldsymbol{y}_2\cdot T/2, \boldsymbol{u}_{k+1/2}, t_k + T/2) \\ \boldsymbol{y}_4 = \boldsymbol{f}(\boldsymbol{x}_k + \boldsymbol{y}_3, \boldsymbol{u}_{k+1}, t_{k+1}) \end{cases} \tag{3}$$

where, for simplicity, $t_{k+1}=t_k+T$, $\boldsymbol{x}_k=\boldsymbol{x}(t_k)$, $\boldsymbol{u}_k=\boldsymbol{u}(t_k)$, $\boldsymbol{u}_{k+1/2}=\boldsymbol{u}(t_k+T/2)$, $\boldsymbol{x}_{k+1}=\boldsymbol{x}(t_k+T)$, $\boldsymbol{u}_{k+1}=\boldsymbol{u}(t_k+T)$. Taking into account that the input quantity changes much slower than the state quantity in flight control, $\boldsymbol{u}_{k+1/2}$ and $\boldsymbol{u}_{k+1}$ are set to $\boldsymbol{u}_k$ when implementing the program.

4. Module design based on Unity3D

After receiving the flight parameters updated by the numerical solution algorithm, Unity3D part re-displays dynamically the aircraft motion state and other parameters. It is also responsible for receiving experimental settings, saving experimental results, visualizing experimental content, updating mathematical models passed to the numerical solution algorithm, etc. According to the design content, it includes working mode, algorithm interface and human-machine interface module.

4.1. Design of Working Mode

According to whether drive manually, flight control modes are divided into manual control and automatic control modes. Meanwhile, according to whether the control target parameters change in aircraft's symmetric plane, flight control modes are further divided into longitudinal manual control, lateral manual control, longitudinal pitch angle automatic control, longitudinal height automatic control, longitudinal speed automatic control, and automatic control of the lateral rolling angle, automatic control of the lateral heading angle, and automatic control of the lateral deviation.

In different flight control control modes, the state space coefficients shown in equation (1) are different, and the mathematical model passed to the numerical solution algorithm needs to be updated according to the experimental settings. In manual control mode, the mathematical model of the aircraft remains unchanged, and the input quantity changes with the experimental settings. In automatic control mode, not only the input quantity changes with the experimental settings, but also affected by the change of control gains, the mathematical model of the aircraft changes. The working mode module determines the model coefficients according to longitudinal automatic flight control and lateral automatic flight control. In theoretical teaching, the design of longitudinal and lateral automatic flight controllers often adopts the state feedback control form, and the general state feedback control law can be expressed as follows:

$$\boldsymbol{u} = -\boldsymbol{K}\boldsymbol{x} + \boldsymbol{u}_c \tag{4}$$

where, $\boldsymbol{K}$ is the designed control gain matrix, and $\boldsymbol{u}_C$ is the flight control setting input vector, corresponding to various command values. For the assignment of control gain matrix, students can choose one of two ways to determine: (1) default values provided by the platform. students can change the default gain coefficients, compare the system response changes, and select the optimal coefficient; (2) values input by students. According to the aircraft mathematical model, students can use methods such as different methods in Matlab to design the control law, and the corresponding coefficients are set on the platform to visually verify the control effect.

Substitute equation (4) into equation (1) to obtain:

$$\dot{\boldsymbol{x}} = (\boldsymbol{A} - \boldsymbol{B}\boldsymbol{K})\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u}_c \tag{5}$$

As can be seen from equation (5), the model is still in the state space form after being controlled, and the aforementioned numerical solution algorithm can be used for the solution.

In the experiment, the control law coefficients and control commands of longitudinal automatic flight control and lateral automatic flight control can be modified through the human-machine interface. After the working mode module determines the model coefficient according to the state feedback control, it will be sent to the algorithm interface for flight parameter solution and update. .

4.2. Design of Algorithm Interface

The algorithm interface involves the communication design between Unity3D part and high-level language program part. The working mode module passes the updated model coefficients to the numerical solution algorithm at the visual refresh rate, and uses the numerical solution algorithm shown in equation (3) to solve the model. Then, the results are returned to Unity3D part.

The main problem here is to determines the communication rate based on the Unity3D visual refresh rate and step size of the algorithm. In order to ensure that Unity3D part can correctly display the control effect of the working mode, the following factors need to be considered: (1) The visual refresh rate cannot be too slow because the display needs to be continuous and without a sense of jump, and it cannot be too fast to prevent Unity3D from being unable to respond. (2) The visual refresh rate should meet the needs of numerical simulation for description of flight motion characteristics. Generally, it is chosen as more than 10 times the fastest natural response frequency of the aircraft. In this paper, the fastest natural response frequency of the aircraft model is 18.6 Hz, so the sampling period should be less than 5.38 ms. Finally, the visual refresh period is set to 5ms. (3) When solving numerical values, step size of the algorithm is a logical simulation time. The algorithm is prone to divergence when step size is set too large, and computing power is required too high when step size is set too small. Since the numerical solution algorithm only needs to pass the results to Unity3D part when the visual refresh period arrives, the step size can be different from the Unity3D visual refresh period. Here, the step size T is fixed to 0.1ms.

4.3. Design of Human-machine Interface

The human-machine interface provides a interface between students and the functions of the platform as shown in Figure 2. The platform provides human-machine interfaces for three categories of experiments: (1) Spatial motion cognition. It can help students better understand the basic concepts of flight control, flight control mechanism, flight control components. (2) Manual flight control. It can help students better understand the impact of flight control mechanisms on aircraft motion. (3) Automatic flight control. It can help students become more familiar with flight instruments, analyze different flight control modes and understand their roles.

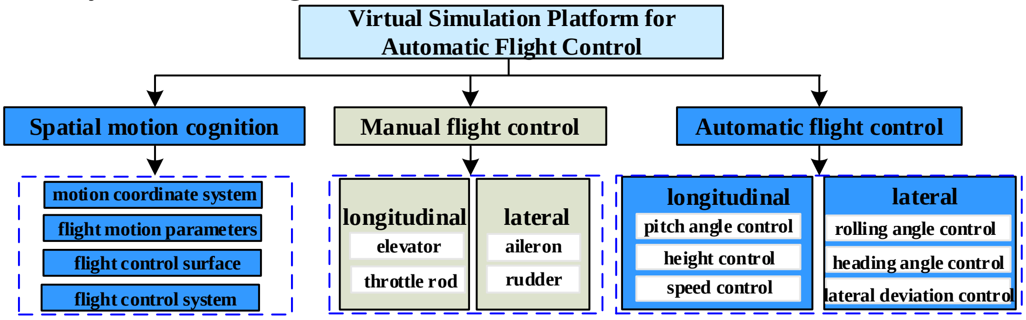

Figure 2 Functional block diagram of virtual simulation platform for automatic flight control

The main interface layout of the platform is similar to Figure 3. Three categories of experimental options and experimental options are shown in the top, as well as the specific experimental content. Figure 3 shows one interface for spatial motion cognition. Basic concepts of flight control, flight control mechanism, flight control components are explained in three-dimensional visualization.

Figure 3 Experimental interface of "Flight Control System" in "Spatial Motion Cognition"

The experimental interface of categories of manual flight control and automatic flight control are similar. Figure 4 shows one interface of altitude automatic flight control. Here, flight parameters under different control setting are shown in the forms of digital, curve, and instrument display.

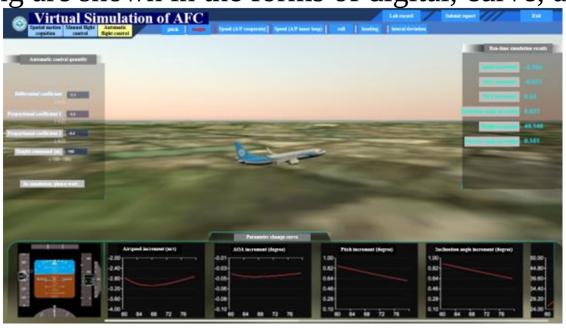

Figure 4 Experimental interface of " Height Control" in "Automatic Flight Control"

5. Virtual Simulation Applications

The platform is deployed on the virtual simulation experimental teaching project exhibition platform of the Civil Aviation University of China. Based on the platform, three types of experiments are set up: spatial motion cognition, manual flight control, and automatic flight control. Students should follow the following steps to perform experiments:

(1) Student downloads the client from the virtual simulation experimental teaching project exhibition platform of the Civil Aviation University of China;

(2) Student run the client and click one of the three modules of the main interface as shown in Figure 3 to enter one type of experiments;

(3) When "Spatial Motion Cognition" is selected, a basic concept explanation and corresponding pictures are given to help student understand the basic concepts;

(4) When "Manual Flight Control" or "Automatic Flight Control" is selected, set the simulation parameters and run client, student can visualize the changes in the aircraft motion state and observe the changing of flight parameters as shown in Figure 4. It help student understand the functions of flight control system, as well as analysis flight control laws. The results of each experiment can be saved for comparison and analysis, and the experimental recording window is shown in Figure 5;

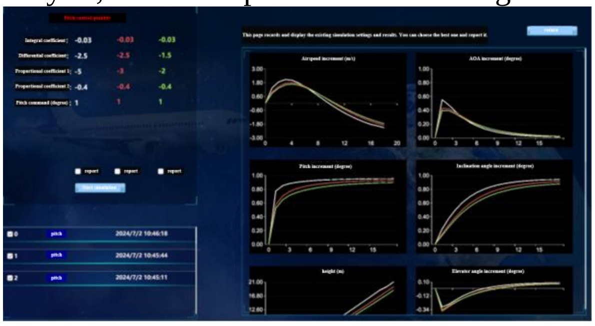

Figure 5 Experimental recording window for comparison of results

(5) After the experiment is completed, student upload records to the exhibition platform with the experimental data. On this basis, teachers can further analyze the grades and experimental data to obtain an analysis of students' experimental ability.

The developed simulation platform have been applied and practiced for two semesters in the major of electronic information engineering. Students generally reflect that the platform visualizes the connection between flight control system and aircraft motion state, deepens their understanding of the flight control principles and systems. Some typical feedback suggestions are as follows:

(1) Virtual simulation experiments are not restricted by time and space, and flight control experiments can be carried out anytime and anywhere for easy learning.

(2) Taking civil aircraft flight control system as the object, it is more closely related to aircraft practice and theoretical learning, visulizes the control effects, and generally improve learning enthusiasm and initiative.

(3) The experimental guidance and exercises in the platform are of great help to understand the experiment. It is recommended to further enrich the flight control systems and experimental test questions of different aircraft models.

6. Conclusion

Based on the creation engine Unity3D, combined with the mathematical model before and after the aircraft is controlled and numerical solution algorithm, a virtual simulation platform for automatic flight control was developed under the guidance of experimental teaching requirements.

Based on the dynamics model of typical theoretical teaching models, this experimental platform is more closely related to theoretical teaching, which facilitates the verification of theoretical analysis. At the same time, the platform can support basic concept explanations of flight control, flight control mode, and automatic flight control law design experiments, which is conducive to students being familiar with the flight control system of typical aircraft, understanding the flight control principles and improving flight control design capabilities, making it easier to carry out online teaching and sharing teaching resources.

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