Design of Flight Closed Loop Simulation System Based on Runge-Kutta Algorithm

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Abstract. To solve the problem that the function/performance of the module cannot be fully verified in the laboratory or in the field during the design stage of the airborne radar system, the paper proposes and designs an airborne flight closed-loop simulation system. The flight simulator, which is the core of the entire simulation system, uses the Runge-Kutta algorithm to solve the model and solve the 6-degree-of-freedom nonlinear model of the aircraft in real time, providing realistic aircraft movement data for the airborne radar system. The design builds a Matlab/Simulink simulation model and embeds it in simulation test software to run independently as a model component. The verification test of the closed-loop simulation system shows that the system can realize the real-time simulation of the entire flight environment and meet the design performance requirements.

1. Introduction
With the development of modern science and technology, the airborne radar system has become a key avionics equipment for various military and civil aircraft, and the functions of the airborne radar are becoming more and more powerful. It not only has the traditional air target detection and fire control guidance functions, but also can realize multi-target tracking, terrain detection and mapping, terrain following/terrain avoidance, weather detection, and low-altitude collision avoidance[1]. Modern airborne radar systems are also becoming more and more complex, the information being processed is becoming larger and larger, and the development is becoming very challenging.

At present, due to the lack of corresponding simulation verification means in the design and development stages, it is not possible to fully verify the function/performance of the above modules in the laboratory or in the field. Therefore, it is urgent to establish an airborne flight closed-loop simulation system which can build a closed-loop simulation test environment for the entire radar[2][3]. Radar model simulation generates airborne radar ranging and angle measurement signals. Carrying on-board radar-in-the-loop hardware-in-the-loop simulation testing can effectively verify the radar hardware and software design and algorithm design. This is of great significance for reducing the development cycle, reducing the cost and the risk of flight test[4].

2. System architecture
The composition of the flight closed-loop simulation system is shown in the following figure1.

Flight closed-loop simulation system includes flight simulator, embedded electronic disk reading and conversion module, whole-machine closed-loop simulation test software, steering rod/pedal control mechanism, etc. Among them, the flight simulator is the core of the entire "flight simulation and closed-loop simulation system", which solves the 6-degree-of-freedom dynamic model of the
aircraft, which can realistically simulate the attitude and speed of the aircraft during flight[5]. The aircraft model is also a key part of it, and the quality of the model directly affects the operating results of this simulation model.

3. Function development

3.1. Flight simulator design

The flight simulator is the core of the entire simulation system. It can solve the 6-degree-of-freedom nonlinear model of the carrier aircraft in real time, and provide realistic carrier motion data for the airborne radar system, including the carrier's position, attitude, speed, acceleration, and angular velocity. These data are the basic data of the inertial navigation model. The inertial navigation model solves the inertial navigation output signal, and then sends it to the carrier radar by the 1553b bus for the carrier radar navigation algorithm. At the same time, the flight simulator collects steering rod/pedal and other manipulation commands, solves the stability-enhancing control law model, and realizes the tester's control of the aircraft. The radar model solves the echo data of the target and terrain in front of the carrier based on the digital map and the air target, and sends it to the embedded electronic disk reading and conversion module[6].

The configuration of the flight simulator is as follows:
- Hardware: Portable industrial control computer, 1553b interface card
- Software: 6 DOF nonlinear aircraft model, Inertial navigation and other avionics models, Digital mapRadar model, Flight control model, Simulation target machine management software, Communication interface software
3.2. Simulation software design

Simulation test software is a drawing software used for the management, control and data analysis of the entire project. It includes: flight simulator control software module, radar test flight data playback control software module, test data analysis and drawing software module.

1) The flight simulation control software implements functions such as start and stop control of the flight simulator, automatic code generation of the simulation model, model download, simulation process control, and radar air target setting.

2) The data analysis and drawing software realizes the analysis and drawing of the test data for the reference of the test engineer.

3) Radar test flight data playback control software can help users choose to playback test flight data stored in the electronic disk.

4. Key technologies

4.1. Runge-Kutta algorithm

The aircraft model in the flight simulator needs to solve the 6-degree-of-freedom dynamic model. We use the Runge-Kutta algorithm to solve the model. The characteristics of the Runge-Kutta algorithm are: the amount of simulation calculation and the simulation step size h is closely related. The smaller the value of h, the higher the calculation accuracy, but the more simulation steps required for a specific time period, the greater the amount of calculation[7]. The fourth-order Runge-Kutta algorithm actually takes the first five terms of the \( y(t) \) Taylor series expansion, so its single-step truncation error is \( O(h^5) \), so the algorithm has a fourth-order accuracy. Compared with the Euler method and the improved Euler method, it has obvious advantages in accuracy[8][9].

The following is the Runge-Kutta algorithm to solve the differential equations of six-degree-of-freedom carrier motion. The recursive formula for the fourth-order Runge-Kutta algorithm is:

\[
\begin{align*}
  y_{k+1} &= y_k + \frac{h}{6}(k_1 + 2k_2 + 2k_3 + k_4) \\
  k_1 &= f(t_k, y_k) \\
  k_2 &= f\left(t_k + \frac{h}{2}, y_k + \frac{h}{2} k_1\right) \\
  k_3 &= f\left(t_k + \frac{h}{2}, y_k + \frac{h}{2} k_2\right) \\
  k_4 &= f(t_k + h, y_k + h k_3) \\
\end{align*}
\]

(1)

4.2. Matlab/Simulink model

Design and implement the above model in Matlab/Simulink, as shown in the following figure 2, and embed it in the simulation test software to run independently as a model component.

The model solving process is as follows: After the external device sends out the control command, the aircraft simulation model receives the control data, and then enters the calculation process. The simulation model is established according to the aircraft flight dynamics principle, and the movement state of the aircraft is calculated according to a certain process, including its position, attitude, speed and angular velocity. After the control data is converted, the model calls the basic parameters of the aircraft, calculates the local atmospheric parameters, and then calculates the aerodynamic force received by the aircraft to obtain all the forces and moments acting on the center of gravity of the aircraft, and forms the equation of motion. By solving the equation of motion, the motion state of the aircraft is obtained. The output of the simulation model is the spatial position and motion state of the converted aircraft.

The simulation model processing flow chart is shown in figure 3.
Figure 2. Matlab/simulink model implementation

Figure 3. Flow chart of simulation model
5. Results and verification

By combining with actual products and related data, the closed-loop simulation system is verified and tested, as shown in figure 4. The results show that the closed-loop simulation system can successfully achieve real-time simulation of the entire flight environment, and various technical indicators have also reached the design performance.

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