A Fast Calculation and Rendering Method for Infrared Characteristics of Hypersonic Vehicle

Chenying Bao¹, Ni Li¹, Guanghong Gong¹, Chao Tian² and Yuanjie Lu³

¹ School of Automation Science and Electrical Engineering, Beihang University, Beijing 100191, China
² Sichuan Aossi Technology Co., Ltd., Chengdu 610094, China
³ Chinese Aeronautical Establishment, Beijing 100029, China

*Correspondence Author: baochenying@buaa.edu.cn

Abstract. In this paper, a fast calculation and rendering method for infrared characteristics of hypersonic vehicle is proposed, which covers the overall infrared simulation process. The key point of this method is the heterogeneous interpolation algorithm, which can map the data from dense grid to sparse grid, thus greatly reducing the volume of data and improving rendering efficiency on the premise of guaranteeing the simulation reliability. Taking the hypersonic vehicle X-43A as an example, we realize the calculation and rendering of its infrared characteristics. Experimental results show that the infrared radiation characteristics of hypersonic vehicle are primely reproduced in the rendering process.

1. Introduction

Hypersonic vehicle has received extensive attention from space powers around the world and is the forefront of the current development of aerospace technology [1]. Since the flight speed of hypersonic vehicle is more than 5 Mach, strong friction occurs between the skin of the aircraft and the airflow, resulting in temperature rise and intense infrared radiation [2]. However, the real flight test of hypersonic vehicle is costly and complicated, and it is difficult to obtain the measured data. In order to further predict the infrared radiation law of hypersonic vehicle under various conditions, and to provide a reference for aircraft design and thermal protection, it is necessary to model and simulate its infrared radiation characteristics.

The infrared radiation characteristic of an aircraft refers to the infrared spectral radiation intensity generated by the aircraft as an infrared target. The infrared radiation of the aircraft mainly comes from the aerodynamic heating of the aircraft skin and the exhaust system of the engine. The infrared radiation band of the aircraft skin is 8 ~ 14 μm, which is the main detection range of modern infrared tracking systems [3]. Therefore, we mainly consider the infrared radiation of aircraft skin in this paper. However, it is difficult to model the infrared characteristics of hypersonic vehicle because of its complex aero-thermodynamic environment. Researchers usually apply CFD (Computational Fluid Dynamics) methods to obtain the surface temperature data of hypersonic vehicle, and further calculate the infrared radiation.

With the continuous improvement of computer hardware, CFD has been gradually applied in the infrared simulation of aircraft. Belgium Defense Establishment Center developed an open source software OSMOSIS, which used CFD to calculate the infrared radiation characteristics of ships, and was eventually extended to aircraft [4]. Culler [5] proposed a new coupled model of fluid mechanics,
thermodynamics and structure to analyse the coupled heat transfer simulation of hypersonic aircraft. Xu Dingguo [6] calculated the infrared radiation intensity distribution of a typical combat aircraft at $8 \sim 14 \mu m$ band by using the discrete transfer method, combined with CFD calculation of the ejector nozzle of a turbofan engine. Yinfen Xie [7] applied parallel computing to CFD calculation, which effectively improved the efficiency of solution. Zhou Fangfang [8] comprehensively considered the influence of the target's motion state and atmospheric environment, and established a three-dimensional temperature field model of the target by using FLUENT software, taking the aircraft model X-51A as an example. These studies provide effective references for the establishment of the infrared characteristic model of hypersonic vehicle.

However, the use of CFD for aircraft temperature calculation requires a very high geometric mesh density, resulting in large volume of surface temperature data and slow rendering efficiency. In order to realize fast visualization of infrared radiation characteristics, we propose a fast calculation and rendering method for infrared characteristics of hypersonic vehicle, with the main flowchart shown as figure 1. The key point of this algorithm is to realize the mapping from dense grid to sparse grid through heterogeneous interpolation, so as to reduce the amount of data, save the cost of calculation, and improve the rendering efficiency on the premise of guaranteeing the simulation reliability.

Figure 1. Flow chart of infrared characteristic simulation

In this article, we take X-43A (a hypersonic test machine developed by NASA) as the research object, and accomplish the calculation and rendering of its infrared characteristics. As shown in figure 1, the entire process can be divided into four main steps. Firstly, obtain surface temperature data through CFD calculations. Secondly, sparse the temperature data through heterogeneous interpolation. Thirdly, calculate the infrared radiation intensity. Finally render the infrared radiation characteristics based on Unity3D. These steps will be explained in detail in the following sections.

2. Temperature data preparation

2.1. Geometric model

We generate the geometric model of X-43A by the NURBS (Non-Uniform Rational B-Splines) technology, as shown in figure 2, with the airframe length of 3.6 meters and the maximum wingspan of 1.52 meters. And further the temperature data is attached to the geometric data points.

Then the flow field division is performed (see figure 3). The total length, width and height of the flow field are 5.2m, 3m and 1.8m, which can cover the variation range of air flow around the aircraft.
2.2. CFD calculation

In this paper, the CFD software FLUENT is used to calculate the temperature field distribution of the aircraft. In order to ensure the accuracy of shock wave capture in compressible flow, we choose density-based solver. Calculation parameters are listed in Table 1.

| Parameter                        | Parameter values |
|----------------------------------|------------------|
| Flight altitude $H$              | 30000 m          |
| Mach number $Ma$                 | 7 Mach           |
| Angle of attack $\alpha$        | 0°               |
| Angle of sideslip $\beta$       | 0°               |
| Air density $\rho$               | Ideal gas        |
| Atmospheric temperature $T$      | 226.65 k         |
| Atmospheric pressure $P$         | 1170 Pa          |

After the CFD calculation, we obtain the surface temperature data of X-43A, and the temperature distribution is shown in figure 5. It can be observed that the aircraft's leading edge, air intake and wake area have obvious temperature increases, which is caused by the special geometric shape design of X-43A. After contacting the lower edge of the aircraft, the air passes through multiple slopes and flows to the air inlet of the supersonic ram engine at a very high speed. The leading edge, air intake and tail of the aircraft are in severe friction with the airflow, which causes the temperature increase and also greatly affects the infrared radiation characteristics of X-43A.
Extract surface temperature data of X-43A from the CFD calculation result, and convert it into Tecplot format for storage. The first half of the data stores the coordinates \((x, y, z)\) of the surface polygon grid points and the corresponding temperature values, and the second half of the data stores the connection relationship between the surface polygon grid points.

It should be noted that, at this time, the temperature data is attached to the dense polygon grid of the aircraft surface. Next, we will sparse the temperature data through the heterogeneous interpolation algorithm introduced in section 3.

3. Sparse processing of temperature data

In fact, the number of polygon grid points is too large for 3D rendering. Therefore, we propose an effective heterogeneous interpolation algorithm that maps the temperature data from a dense grid to a sparse grid to reduce the amount of data subsequently rendered. As shown in the figure 6, the number of dense polygon grid points is 916483, and the number of sparse triangle grid points is 26364.

Figure 5. Surface temperature distribution.

Figure 6. The dense polygon grid and the sparse triangle grid.

The heterogeneous interpolation process is shown in figure 7. Three key problems to be solved are: mesh alignment, reference points search, and weight calculation.
3.1. Mesh alignment
In general, mesh alignment of heterogeneous grids is very intricate. But the dense polygon grid and the sparse triangle grid are two different discrete forms of the same original geometric model as shown in figure 2. We only need to adjust the size and position to set the sparse grid and the dense grid approximately in the same spatial position.

3.2. Reference points search
To perform heterogeneous mapping, it is necessary to determine the reference points corresponding to the target mapping point. We design a reference point searching algorithm combining KNN and KD-tree, which can quickly return the indexes of reference points. KD-tree is a data structure that divides multi-dimensional space, and we employ KD-tree to optimize the data storage structure, so as to achieve fast KNN search.

For each point in the sparse grid, we use KNN algorithm to find k nearest neighbor points in the dense grid as the reference points. The distance measurement criterion we select is Euclidean distance.

As shown in figure 7, firstly, read the sparse grid and the dense grid and establish the sparse and dense point queues respectively. Then build a KD-tree for dense point queue. For each point in the sparse point queue, the searching algorithm will automatically find the nearest neighbor points in the KD-tree and return the indexes.

3.3. Weight calculation
After obtaining the reference points, we apply the simplex volume ratio interpolation algorithm to calculate the weight of each corresponding reference point.

Simplex is a generalization of triangle and tetrahedron. An n-dimensional simplex refers to a convex polyhedron containing n+1 nodes. Specifically, one-dimensional simplex is a line segment, two-dimensional simplex is a triangle, and three-dimensional simplex is a tetrahedron. The volume calculation formula of n-th order simplex with vertices \((v_0, ..., v_n)\) is shown in equation (1).

\[
V(v_0, ..., v_n) = \frac{1}{n!} \det(v_1 - v_0 \ v_2 - v_0 \ ... \ v_n - v_0 \ v_n - v_0)
\] (1)

Suppose k reference points are found for each point in the sparse point queue, then the weight of each reference point is expressed as equation (2).

Figure 7. Flow chart of heterogeneous interpolation.
\[ \omega_i = V_i / \sum_{i=1}^{k} V_i \]  

(2)

After the reference point index and the corresponding weight are obtained, the temperature value of the point to be interpolated can be calculated. The calculation formula is shown in equation (3).

\[ T_x = \omega_1 T_1 + \omega_2 T_2 + \cdots + \omega_k T_k \]  

(3)

Where, \( T_x \) is the temperature value of the point to be calculated. \( T_1, T_2, \ldots, T_k \) refer to the temperature value of the 1st, 2nd, ..., k-th reference points. \( \omega_1, \omega_2, \ldots, \omega_k \) refer to the weight of the 1st, 2nd, ..., k-th reference points. Notice that the sum of the weights is equal to 1.

In this paper, we set the number of nearest points to be found at 4. Based on the above heterogeneous interpolation algorithm, we have completed the sparse processing of temperature data. The comparison of point clouds before and after interpolation is shown in figure 8. After sparse processing, the volume of temperature data is reduced to 2.8% of the original, which greatly reduces the computational burden of subsequent rendering.

![Figure 8](image_url)
4. Infrared radiation calculation

Objects above absolute zero will radiate infrared energy. In the process of propagation, infrared radiation will be absorbed and scattered by gas and particles in the atmosphere, and radiation of certain wavelength will decline by degrees in the process of transmission. Under supersonic and hypersonic conditions, infrared radiation at 8-14 μm band is the most significant, and this band is selected as the key simulation band.

At the 8-14 μm band, the calculation formula of infrared radiation characteristics of the aircraft is shown as equation (4).

\[
I_{self}(\varepsilon,T_w)|_{\lambda_1,\lambda_2} = \frac{\varepsilon}{\pi} \int_{\lambda_1}^{\lambda_2} \frac{c_1 \lambda^3}{(e^{\varepsilon/(\lambda T_w)} - 1)} d\lambda
\]

(4)

Where, \( I_{self}(\varepsilon,T_w) \) is the infrared radiation intensity. \( T_w \) is the radiation source temperature. \( \lambda \) is the wavelength of the infrared radiation wave. \( \lambda_1 \) and \( \lambda_2 \) is the upper and lower limit wavelength of the selected infrared band. \( \varepsilon \) is the emissivity of the surface element. \( c_1 \) is the first radiation constant, and \( c_1 = 3.7419 \times 10^{-16} W \cdot m^{-2} \). \( c_2 \) is the second radiation constant, and \( c_2 = 1.4388 \times 10^{-2} m \cdot K \).

5. Infrared radiation characteristics rendering

Unify3D is a cross-platform VR development engine that encapsulates the underlying 3D graphics rendering libraries, such as Direct3D, OpenGL, and supports rendering of large scenes. After calculating the infrared radiation, we implement the infrared radiation characteristics rendering of X43A based on Unify3D. The rendering process is shown in figure 9, which is roughly divided into two parts, one is CPU-based data reading and processing, the other is GPU-based texture mapping and rendering.

5.1. Conversion of infrared data to color data

5.1.1. Grayscale data conversion. In Unify3D, the grayscale information is a floating number between 0 and 1. The larger the value, the higher the brightness (tend to be white). Therefore, the grayscale data can be obtained by mapping the infrared radiation data to the interval from 0 to 1 by using a linear normalization method.
Linear normalization [9] is also called min-max normalization, and the calculation method is shown in equation (5).

\[ x^* = \frac{x - \min}{\max - \min} \] 

(5)

5.1.2. Homogenization processing. In hypersonic flight, the flow field distribution is often distorted at key geometric nodes, resulting in the uneven distribution of infrared field data. The linear normalization method does not change the distribution characteristics of the data, so it is necessary to further homogenize the infrared field data.

In fact, infrared radiation data has been converted into grayscale information after normalization processing, and the uneven distribution of data can be equivalent to the problem of too low contrast in grayscale images, so an image sharpening algorithm is used for homogenization processing.

The algorithm adopted is histogram homogenization, also known as histogram equalization [10], through which the image gray value can be stretched nonlinearly, so as to make the pixel distribution in a certain range even.

After the above processing, we transformed the infrared radiation data into evenly distributed grayscale data, which can be used for texture mapping and rendering in the next step.

5.2. Infrared texture mapping and rendering

In the previous step, we obtained the infrared characteristic information stored in the form of grayscale information uniformly on the surface of the aircraft. Next, we adopted the fragment Shader method based on Unity Shader to simulate the characteristics in the process of infrared radiation divergence. The implementation of this part can be divided into two main techniques: texture mapping and noise superposition.

5.2.1. Texture mapping. Texture mapping refers to the overall control of the rendering scene color, light and shade by inputting different texture images. The pseudo-color texture mapping scheme is adopted in this paper. First, read in the color texture image as shown in figure 10. Then, tex2D function is used to sample the color texture according to the gray scale data to obtain the corresponding pixel color value, so as to render the infrared radiation brightness of the aircraft.

![Figure 10. Color texture.](image)

5.2.2. Noise superposition. In the infrared receiving process, noise is widespread, and usually comes from natural ambient light, artificial ambient light, detector noise, and the inside of the receiving circuit. When simulating an infrared scene, noise should also be considered noise to simulate the effect of receiving the infrared image at different SNR (Signal-to-noise Ratio).

First generate a Berlin noise [11] texture picture as shown in figure 11. Then use the tex2D function to sample the noise texture to render the noise effect.

![Figure 11. Berlin noise texture.](image)
The final rendering result is shown in figure 12. It can be seen that the X-43A hypersonic vehicle generates a large amount of heat in the friction with the air, which is mainly distributed in the leading edge of the aircraft. The rendering process primely reproduces this phenomenon.

![Image](a) ![Image](b)

**Figure 12.** Infrared radiation characteristics rendering effect.

6. Conclusions
In this paper, we present a calculation and rendering method for infrared characteristics of hypersonic vehicle, and implement the overall simulation process that integrated CFD calculation, data processing and rendering. There are two important contributions of this paper. One is the heterogeneous interpolation algorithm, which can realize the data mapping from dense grid to sparse grid, thus greatly reducing the volume of data and improving rendering efficiency. The other is the rendering method based on Unity3D, which can commendably reproduce the infrared radiation characteristics of hypersonic vehicle through texture mapping and noise superposition.

For future works, we will consider the multi-physical field coupling characteristics of hypersonic vehicle to calculate more accurate surface infrared radiation. And more advanced geometric reconstruction method will also be explored to generate the sparse mesh of better quality.

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