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A real-time infrared imaging simulation method with physical effects modeling of infrared sensors

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HIGHLIGHTS

- Real-time simulation to reproduce a complete physical imaging process.
- Generating infrared images with multiple sensor physical effects.
- GPU-based improved image convolution method to enhance real-time ability.

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ABSTRACT

Infrared imaging simulation technology can provide infrared data sources for the development, improvement and evaluation of infrared imaging systems under different environment, status and weather conditions, which is reusable and more economic than physical experiments. A real-time infrared imaging simulation process is established to reproduce a complete physical imaging process. Our emphasis is put on the modeling of infrared sensors, involving physical effects of both spatial domain and frequency domain. An improved image convolution method is proposed based on GPU parallel processing to enhance the real-time simulation ability with ensuring its simulation accuracy at the same time. Finally the effectiveness of the above methods is validated by simulation analysis and result comparison.

1. Introduction

Infrared imaging systems have been widely used in military and civil fields, such as target detection, fault diagnosis, fire detection, and medical diagnosis. During the development process of an infrared imaging system, we need a lot of infrared images obtained under different environment and different meteorological conditions to evaluate and test the performance of the system. Compared to physical test methods, the application of infrared imaging simulation technology is not restricted to specific experimental environment and can help us to get abundant and comprehensive infrared radiation image sources with very low cost. These images can also provide guidance for the development and improvement of infrared sensors to effectively reduce the cost effectiveness.

These advantages of infrared imaging simulation technology makes it appear an important application value in national defense, aviation, aerospace and other fields. Many scholars have carried out a lot of research work and formed a series of models to be applied in design, training and evaluation of actual systems. Some representative infrared imaging systems are Vega Prime IR/NVG Sensor Module [1], CAMEO-SIM [2], SE-WorkBench-IR [3], Mantis ViXsen [4] and ShipIR/NTCS [5]. These mentioned systems mostly take a complete process of infrared imaging into account, involving aspects of target, background, atmosphere environment, and infrared sensor based on accurate physical modeling and mathematical calculation. A lot of achievements have been made in research on the development of typical infrared sensor models based on ray tracing method, image processing method, modulation transfer function (MTF) method, such as SYTHER [6], IGOSS [7], and NVTherm [8]. But there still exist some shortcomings and the problems mainly lying in the comprehensive modeling, real-time performance and simulation accuracy of sensor models. The development trends of infrared sensing models are listed as follows: 1. the implementation of simulation models is increasingly comprehensive, introducing signal responses and space transfer effects of the whole process as much as possible; 2. simulation models are consistent with the real physical process to obtain better accuracy; 3. More and more attention is put on the decoupling characteristics of function modules to achieve an extensible simulation model; 4. high performance parallel

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computing is introduced in order to better solve the contradiction between physical process complexity and real-time simulation; 5. simulation results need to be verified and evaluated to ensure the reliability of these simulation models.

Although the research and application of infrared imaging simulation systems have made a lot of progress, current comprehensive literatures relating to the whole physical modeling and real-time image generation are still very limited. Hence, our paper presents a real-time infrared imaging method to reproduce each link of the infrared imaging chain by considering the complete physical process of an actual infrared imaging system. Furthermore, this method is supposed to support the 3D visualization of infrared characteristic of a virtual scene. The refresh rate measured by FPS (frames per second) should be no less than 25 to avoid screen flicker for real-time 3D graphical rendering. This requires that our physics-based simulation method must have the capability to finish a calculation process within 40 ms when updating working status, environment and sensor parameters. Thus our real-time infrared imaging method aims to achieve an optimal trade-off between simulation accuracy and real-time rendering. The modeling of zero-distance radiation, atmospheric transfer, infrared sensor effect and real-time rendering based on OGRE (Open Source 3D Graphics Engine) are elaborated. Especially various physical effects modeling of infrared sensors is analyzed and discussed comprehensively. Multiple physical effects of both spatial domain and frequency domain are simulated systematically, including the modeling of optical systems, infrared detector systems and signal processing systems. Considering the simulation accuracy and real-time performance of different physical effects, this paper also presents an improved efficient parallel simulation method based on GPU. The decoupling simulation of each physical effect module can support configurable sensor parameters.

The remainder of the paper is organized as follows. In Section 2, a literature review is provided. In Section 3, our real-time infrared imaging simulation process is introduced. In Section 4, a modeling framework for infrared sensor effects is proposed which integrates the physical effects modeling of both spatial and frequency domain. The simulation results with different sensor parameters are analyzed in Section 5. In Section 6, a summary is presented.

2. Literature review

Along with the deepening of research, physical infrared models have been widespread concerned by governments and research institutions. With substantial financial support, several typical infrared prediction models were developed. Physically Reasonable Infrared Signature Model (PRISM) was developed by U.S. Army Tank – Automotive Command in 1988. PRISM is a first principle semi empirical model developed for but not limited to thermally modeling vehicles [9]. In 2013, C.Q Gao proposed a new infrared patch-image model using local patch construction. The model not only worked more stably for different target sizes and signal-to-clutter ratio values, but also had better detection performance compared with conventional baseline methods [10]. Then, in 2015, Sean Archer studied a Digital Imaging and Remote Sensing Image Generation (DIRSIG) Model. Within it, he proposed a micro-scale surface property model (microDIRSIG) and utilized radiative transfer modeling to generate synthetic imagery [11].

As an important part of Infrared imaging system, in recent decades, sensor modeling is concerned by researchers gradually. One of the sensor modeling tools called SYTHER (Synthesis of THERmal images) was developed by DASSAULT AVIATION. SYTHER's purpose was to generate realistic synthetic images of scenes made of landscapes and targets observed by a wide range of sensors in any IR waveband and in any environmental condition [12]. A model for Image Generation in Optronic Sensor Systems (IGOSS) was developed at the Defence Research Establishment in Sweden in 1998 [7]. IGOSS can model the effects of vibrations, the optics, detector, processing unit, the display and transversal movement of a sensor platform and a separate target in the background image by calculating their MTFs [13]. In 2000, Mohammad S. Alam calculated the MTF value of optical systems and detectors system with noise effects and he proposed an effective means of removing the blur caused by the system MTF and improving the resolution of micro-scanned image data [14]. Based on imaging system parameters, Liu et al. raised a new infrared sensor model and its specific MTF expressions which took sensor physical effects into consideration [15]. As a high-resolution imaging system, Image Based Sensor Model (IBSM) was developed by Environmental Research Institute of Michigan in 1996, which is a modular set of numerical tools for designing, evaluating, and modeling electro-optical and infrared imaging sensors [16]. IBSM could produce simulated sensor imagery in addition to sensor performance metrics to better characterize the imaging performance of a sensor system [17].

Most articles mentioned above are aiming at providing precise physical models without considering the simulation efficiency as a key factor. We draw more attention on infrared image rendering efficiency and at the same time we adopt a physics-based modeling method to ensure the simulation accuracy. Although a lot of work has been done about the MTFs of sensor effects, study on the impact on real-time imaging with different MTFs and sensor parameters is still rare. Compared with other predecessors, we try to integrate twelve different effects existed in three major sub-systems of sensor and the superimposition of various effects is achieved. To provide a more efficient simulation method with high precision, an improved rhombus kernel for imaging revolution is proposed. In addition, a parallel computing method using GPU is introduced to accelerate computation speed.

3. A real-time infrared imaging simulation process

Our real-time infrared imaging simulation process is shown in Fig. 1, including zero-distance radiation modeling, atmospheric transmission modeling and infrared sensor modeling. A loose coupling structure is adopted here for the independent implementation and performance analysis of each module. It is also conducive to the interaction and integration based on data flow. We use OGRE, which is an open source 3D graphics rendering engine, to complete 3D scene management, resource management and graphics rendering.

The zero-distance radiation modeling is the basis of generating an infrared image. The temperature field and radiation field of a target can be solved by establishing a heat balance equation. A 3D model should be established according to its structure characteristics of the target, which also provides divided meshes for equation solving. Inputs of the zero-distance radiation model are the target's working status and environment status parameters; while its outputs are the target's surface temperature field and the corresponding infrared radiation intensity. Take the radiation model of an armored vehicle for an example. According to its structure, a geometrical model is established including 178,190 vertices and four regions, which are firing part (gun barrel and gun turret), driving part (caterpillars), top board of power compartment, and other surface part. For each surface part, we need to establish its heat balance equation according to its convective boundary condition, radiation boundary condition and its working states. The heat balance equation of the top surface part of power compartment is shown in Eq. (1):

$$E_{sun} + E_{sky} + E_{earth} + E_{engine} = E_{radiation} + E_{convection} + E_{\mathrm{internal}} \tag{1}$$

where E_{sun}, E_{sky}, E_{earth} denote absorbed energy from solar radiation, sky radiation and terrestrial radiation respectively, E_{engine} is the