Fast flux density distribution simulation of central receiver system on GPU

Caitou He\textsuperscript{a,} Jieqing Feng\textsuperscript{a,} Yuhong Zhao\textsuperscript{b,}\textsuperscript{a}

\textsuperscript{a} State Key Laboratory of CAD \& CG, Zhejiang University, Hangzhou 310058, China
\textsuperscript{b} Institute of Industrial Process Control, College of Control Science and Engineering, Zhejiang University, Hangzhou 310027, China

\textbf{Abstract}

The simulation of the light flux density distribution on a receiver plays an important role in energy estimation, design and optimization of a heliostat field and the focusing strategy for a central receiver system (CRS). However, this simulation is a time-consuming procedure. In this paper, we propose a fast simulation method that fully exploits the tremendous rendering and parallel computing capacities of contemporary graphics processing units (GPUs). First, an auxiliary spatial data structure is employed to organize the heliostats in the field, and a parallel light beam traversal algorithm is designed and performed on the GPU to determine the shadowing and blocking heliostats for each reference heliostat. Then, the flux spot reflected by each heliostat on the receiver is computed using the HFLCAL model and accumulated for the final flux density distribution. Both the computing stage and accumulation stage are accomplished via GPU rendering pipeline. The proposed method is verified by taking the PS10 power plant as an example. Because this method considers both shadowing and blocking effects, the simulation results are consistent with those in the official report. Due to its high efficiency, the proposed method has potential applications in CRS design and optimization.

\section{1. Introduction}

Solar thermal power plants with central receiver systems (CRSs) \citep{Vant-Hull_Hildebrandt_1976} are attracting increasing attention from both the academic and industrial communities. In this system, hundreds or thousands of heliostats reflect sunlight and focus this sunlight onto the receiver to heat a working medium in order to generate electricity. When designing a CRS, many stages and factors influence the electrical generation efficiency. Among these factors, the simulation of the flux distribution on the receiver surface is a fundamental problem \citep{Biggs_Vittitoe_1976}.

There are two main types of flux distribution simulation methods, i.e., the ray tracing approach and the analytical approach. Based on these methods, many practical simulation tools have been developed and released, including SolTrace by NREL \citep{Wendelin_2003}, STRAL by DLR (German Aerospace Center) \citep{Belhomme_2009}, and TieSOL by Tietronix \citep{Izygon_2011}. Among these methods, accuracy and efficiency are always contradictory. The ray tracing approach computes the flux distribution on a receiver by tracing millions of rays or more between the heliostat field and receiver. Obviously, its computational complexity is very high. The analytical approach efficiently evaluates the flux using an empirical analytical formula. Shadowing and blocking effects are difficult to fully take into account, which is one of the reasons that the analytical approach is less accurate than the ray tracing approach.

In this paper, a fast and accurate analytical simulation approach is proposed, that considers both shadowing and blocking effects. The main idea is to convert the computation of the flux spot on the receiver surface contributed by each heliostat into a rasterization procedure through rendering pipeline on graphics processing units (GPUs), i.e., “drawing” the flux spot on the receiver surface, as shown in Fig. 1. The flux accumulation is accomplished via the alpha blending operation \citep{Wallace_1981} in the rendering pipeline. Furthermore, the shadowing and blocking effects are processed in parallel on the GPU. As a result, the proposed method can accurately simulate the flux density of a field containing hundreds of heliostats within dozens of milliseconds.

The rest of the paper is organized as follows: The related work is briefly introduced in Section 2. Some relevant preliminary knowledge is presented in Section 3. The proposed fast flux density distribution simulation method using a GPU is described in detail in Section 4. Validation, experiments and discussion are given in
Section 5. Finally, in Section 6, the conclusions are drawn, and future work is proposed.

2. Related work

2.1. Simulation of flux distribution on the receiver

Basically, two types of flux distribution simulation methods exist: the ray tracing method and the analytical method. Instead of simulation, the flux mapping method measures the flux distribution on the receiver directly; this method is based on the measurement equipment and the image processing techniques. Garcia et al. (2008) gave a detailed comparison between the ray tracing approach and the analytical approach and also provided an overview of relevant simulation tools. Bode et al. (2012), from the South African Solar Thermal Energy Research Institute, gave another survey emphasizing the progress of the simulation tools.

Ray tracing method. Ray tracing is an image synthesis algorithm in computer graphics that simulates the light reflection, refraction and scattering among a light source, objects, and a viewer (Glassner, 1989). This method can naturally take shadowing and blocking effects into account for the flux simulation on the receiver surface cast by the parabolic heliostat H2 is shown, where the flux at the corner is eliminated due to shadowing and blocking effects caused by H3 and H1, respectively.

Fig. 1. The flux simulation is performed as a graphics rendering procedure: (a) the receiver surface is treated as the rendering target, and (b) the flux density distribution on the receiver surface is shown, where the flux at the corner is eliminated due to shadowing and blocking effects caused by H3 and H1, respectively.

Test (VSHOT). However, as the author indicated, the simulation speed needs to be improved.

Belhomme et al. (2009) generated the rays directly on the reflective surface of the heliostat and accelerated the bidirectional ray tracing process by exploiting SIMD architecture on a multi-core CPU. Later, they achieved ray tracing speed of more than 60 million rays per second on an 8 core PC (Ahlbrink et al., 2012). It is worth mentioning that they employed two methods to model the surface errors of a heliostat mirror, i.e., the common statistical approach based on the Gaussian distribution of surface normal vectors (Belhomme et al., 2009), and the approach using measured surface normal vectors of high resolution (Ulmer et al., 2011). Izgon et al. (2011) achieved state-of-the-art ray tracing simulation speed by taking advantage of the parallel computing capacities of contemporary GPUs. Tracing 100 million rays took approximately 887 ms using 3 GTX 570 GPUs.

In the reverse ray tracing method (Pancotti, 2007; Chiesi et al., 2013), rays are emitted from the receiver surface rather than the energy source. They are traced from the receiver to the heliostat and finally to the sun. The flux density is obtained by integrating over the corresponding area of the sun model, which is modeled as a Lambertian surface. Chiesi et al. (2013) achieved 52 times faster speed with heterogeneous systems (8 CPUs and two NVIDIA GTX 570 and one GTX 480 graphics cards) compared to multi-core CPUs.

Analytical method. In a mathematical sense, the analytical method is the convolution of the sun brightness profile with the reflective surface slope errors (Dellin, 1979; Walzel et al., 1977). An analytical solution to this problem is not known so far; instead, numerical approximation approaches (Vittitoe and Biggs, 1981; Biggs and Vittitoe, 1976) have been proposed. The HFLCAL model is a simplification of the convolution approach, and was initially
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