Computational Methods for Global Illumination and Visualisation of Complex 3D Environments

SYNOPSIS

Complex three dimensional environments are visualised by rendering images of these environments as seen from different view points. Over the last three decades rendering techniques have been continuously evolving to greater levels of sophistication in terms of the complexity of environments and the realism with which the images are produced. In all image synthesis techniques the fundamental step is computation of the amount and nature of the light from the three dimensional environment reaching the eye in any given direction. Computer graphics rendering techniques carry out this computation by simulating the behaviour of light in the environment. Greater degrees of realism would mean higher correlation between the simulation and the physical world. In the physical world, lighting, reflection and scattering effects are very complicated and subtle. Every object receives light directly from light sources, or indirectly from reflection or scatter by other neighbouring objects. For realistic image synthesis these intra-environmental effects must be modelled in great detail.

This thesis presents the results of a detailed investigation of illumination computation and rendering techniques. The four major contributions of this thesis are:

- A taxonomy of illumination computation methods.
- Particle tracing techniques for global illumination computation.
- The potential equation for illumination computation and the mathematical framework of adjoint equations.
- Demonstration of the practicality of this new class of global illumination computation algorithms.

From a theoretical point of view the primary contribution is the development of a mathematical framework of adjoint equations which provides the basis for all known illumination computation techniques. This mathematical framework consists of two integral equations - the *radiance* and the *potential* equation, which are duals of each other. While the radiance equation has been known in one form or the other to the computer graphics community, the potential equation for illumination has been introduced for the first time in this thesis. The significance and importance of this new mathematical framework stems from the fact that it not only enables us to review and analyse existing methods but also provides the necessary handles for deriving new and efficient algorithms for simulating the behaviour of light in a manner closely correlating to the physical world.

On the practical side we describe new algorithms that simulate the particle model of light using Monte Carlo methods. The basic idea is to simulate the natural stochastic process describing the flight of light particles in a given 3D environment. All algorithms described in this thesis are based on particle tracing technique. The algorithmic improvements made possible by the use of the mathematical framework of adjoint equations are then demonstrated. Compared to previous work these algorithms can handle more general and complex environments. We also present the results of a straight forward implementation of these algorithms showing that these algorithms are computationally tractable.

Organisation of this Thesis

In Chapter 2, the physics of light, its interaction with the environment, and various empirical and physical models of light-environment interaction are presented in a manner palatable to a computer graphics reader. The radiance equation, expressing the radiance of a surface point in terms of the host surface reflectance and the radiance of the surrounding points, is then derived as an integral equation. Lastly the general radiance equation that takes into account participating volumes is formulated.

Chapter 3 is a comprehensive review of the current state of the art in illumination computation. It shows how most of these light behaviour simulation techniques can be seen as different methods of solving the radiance equation. The two basic simulation strategies, gathering and shooting, are discussed. Within each strategy, methods are further categorised based on whether they use a deterministic or a non-deterministic approach. All methods based on the gathering strategy are directly seen as solutions of the radiance equation while methods based on the shooting strategy can only be indirectly derived from this equation. The chapter concludes with the observation that illumination computation by the use of non-deterministic methods based on the shooting strategy had not been throughly explored.

The particle model of light is the most natural candidate for simulation by a method which uses the non-deterministic approach and is based on the shooting strategy. Chapter 4 introduces the first in a class of particle tracing algorithms which simulate the particle model of light to compute global illumination in a three dimensional environment. Monte Carlo basics and the necessary Monte Carlo sampling techniques needed in this simulation are also presented. The results obtained from an implementation of this algorithm are shown and its performance is compared with a simple standard radiosity implementation. The truly progressive nature of the algorithm is illustrated with the help of examples which show how the illumination computations get progressively refined as the simulation proceeds. The algorithmic modifications necessary to handle complex surface geometry and more complex surface emission and reflection behaviour are presented and the various issues relating to rendering the image from the computed illumination are discussed. Finally the variance reduction technique of absorption suppression is used to improve the efficiency of the particle tracing algorithm.

The particle tracing algorithm is inherently capable of being extended, comparatively easily, to more general environments. This is demonstrated in Chapter 5 by showing the changes necessary to handle participating volumes. First the algorithms to efficiently sample the interaction point and track the particle in the participating volume are presented. Next various modelling techniques to model volume elements have been proposed and used for creating representative test environments with participating volumes. A method for image rendering in the presence of participating volumes is also discussed. Finally implementation of variance reduction techniques such as absorption suppression, forced collision, and particle divergence and their effects have been analysed.

The primary theoretical contribution of this thesis, the potential equation and the mathematical framework of adjoint illumination equations is the topic of Chapter 6. Using intuitive concepts the potential equation is derived and its duality with the radiance equation is proved. That all shooting strategy methods, including progressive radiosity and particle tracing, can be naturally derived as solutions to this potential equation is shown next. The efficiency of the particle tracing algorithms can be increased by the use of suitably transformed probability distribution functions. A number of biasing schemes are devised for this purpose. Implementation issues are discussed and the performance improvements obtained from a simple straight forward implementation are presented.

Chapter 7 is the concluding chapter. The results of the research are analysed along a number of important dimensions such as environmental complexity, image rendering, implementation considerations and relationship with other work. Possible extensions to the method and potential avenues for future research are also briefly discussed.

Computation and measurement in any discipline require a thorough knowledge of the metrics involved. Appendix A, has been devoted to a brief discussion of various light metrics. Light being a form of radiant energy, the discussion starts with metrics used in radiometry, i.e. the measurement of radiant energy. Light is that portion of the vast spectrum of the electromagnetic radiation which generates a physical sensation in the eye. Hence light is also known as visible radiation. The extent of this sensation is dependent on the nature and the amount of visible radiation energy impinging on the eye. The slightly different but related set of metrics that are used for photometry i.e. the measurement of the light based on the visual responses, are then presented. Lastly the highly intuitive term brightness is formally related to *radiance/luminance*, luminance being the photometric equivalent of radiance.